

Detection of CH₃⁺ in the O-rich planetary nebula NGC 6302

CHARMI BHATT,^{1,2} JAN CAMI,^{1,2,3} ELS PEETERS,^{1,2,3} NICHOLAS CLARK,¹ PAULA MORAGA BAEZ,⁴ KEVIN VOLK,⁵ G. C. SLOAN,^{5,6} JOEL H. KASTNER,^{4,7,8}
HARRIET L. DINERSTEIN,⁹ MIKAKO MATSUURA,¹⁰ BRUCE BALICK,¹¹ KATHLEEN E. KRAEMER,¹² KAY JUSTTANONT,¹³ OLIVIA JONES,¹⁴
RAGHVENDRA SAHAI,¹⁵ ISABEL ALEMAN,¹⁶ MICHAEL J. BARLOW,¹⁷ JERONIMO BERNARD-SALAS,^{18,19} JORIS BLOMMAERT,²⁰ NAOMI HIRANO,²¹
PATRICK KAVANAGH,²² FRANCISCA KEMPER,^{23,24,25} ERIC LAGADEC,²⁶ J. MARTIN LAMING,²⁷ FRANK MOLSTER,²⁸ HEKTOR MONTEIRO,^{29,30}
ANITA M. S. RICHARDS,³¹ N. C. STERLING,³² MARYAM TORKI,²³ PETER A. M. VAN HOOF,³³ JEREMY R. WALSH,³⁴ L. B. F. M. WATERS,^{35,36}
ROGER WESSON,^{29,17} FINNBAR WILSON,²⁹ NICHOLAS J. WRIGHT,³⁷ AND ALBERT A. ZIJLSTRA^{31,38}

¹*Department of Physics and Astronomy, University of Western Ontario, London, Ontario, Canada*

²*Institute for Earth and Space Exploration, University of Western Ontario, London, Ontario, Canada*

³*SETI Institute, Mountain View, CA, USA*

⁴*Center for Imaging Science, Rochester Institute of Technology, Rochester NY 14623, USA*

⁵*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*

⁶*Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255, USA*

⁷*School of Physics and Astronomy, Rochester Institute of Technology, Rochester NY 14623, USA*

⁸*Laboratory for Multiwavelength Astrophysics, Rochester Institute of Technology, Rochester NY 14623, USA*

⁹*Department of Astronomy, University of Texas at Austin, Austin, TX 78712, USA*

¹⁰*Cardiff Hub for Astrophysics Research and Technology (CHART), School of Physics and Astronomy, Cardiff University, The Parade, Cardiff CF24 3AA, UK*

¹¹*Department of Astronomy, University of Washington, Seattle, WA 98195-1580, USA*

¹²*Institute for Scientific Research, Boston College, 140 Commonwealth Avenue, Chestnut Hill, MA 02467, USA*

¹³*Chalmers University of Technology, Onsala Space Observatory, S-439 92 Onsala, Sweden*

¹⁴*UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK*

¹⁵*Jet Propulsion Laboratory, 4800 Oak Grove Drive, California Institute of Technology, Pasadena, CA 91109, USA*

¹⁶*Laboratório Nacional de Astrofísica, Rua dos Estados Unidos 154, Bairro das Nações, Itajubá, MG 37504-365, Brazil*

¹⁷*Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK*

¹⁸*ACRI-ST, Centre d'Études et de Recherche de Grasse (CERGA), 10 Av. Nicolas Copernic, 06130 Grasse, France*

¹⁹*INCLASS Common Laboratory, 10 Av. Nicolas Copernic, 06130 Grasse, France*

²⁰*Astronomy and Astrophysics Research Group, Department of Physics and Astrophysics, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium*

²¹*Academia Sinica Institute of Astronomy and Astrophysics, 11F of Astronomy-Mathematics Building, AS/NTU, No.1, Sec. 4, Roosevelt Road, Taipei 106319, Taiwan, R.O.C.*

²²*Department of Physics, Maynooth University, Maynooth, County Kildare, Ireland*

²³*Institut de Ciències de l'Espai (ICE, CSIC), Can Magrans, s/n, E-08193 Cerdanyola del Vallès, Barcelona, Spain*

²⁴*ICREA, Pg. Lluís Companys 23, E-08010 Barcelona, Spain*

²⁵*Institut d'Estudis Espacials de Catalunya (IEEC), E-08860 Castelldefels, Barcelona, Spain*

²⁶*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange, 96 Bd de l'Observatoire, 06300 Nice, France*

²⁷*Space Science Division, Naval Research Laboratory, Code 7684, Washington, DC 20375, USA*

²⁸*Leidse instrumentmakers School, Einsteinweg 61, 2333 CC Leiden, Netherlands*

²⁹*Cardiff Hub for Astrophysics Research and Technology (CHART), School of Physics and Astronomy, Cardiff University, Cardiff CF24 3AA, UK*

³⁰*Instituto de Física e Química, Universidade Federal de Itajubá, Av. BPS 1303, 37500-903 Itajubá, MG, Brazil*

³¹*Jodrell Bank Centre for Astrophysics, Department of Physics & Astronomy, The University of Manchester, Oxford Road, Manchester M13 9PL, UK*

³²*University of West Georgia, 1601 Maple Street, Carrollton, GA 30118, USA*

³³*Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium*

³⁴*European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching, Germany*

³⁵*Department of Astrophysics/IMAPP, Radboud University, PO Box 9010, 6500 GL Nijmegen, The Netherlands*

³⁶*SRON Netherlands Institute for Space Research, Niels Bohrweg 4, 2333 CA Leiden, The Netherlands*

³⁷*Astrophysics Research Centre, Keele University, Newcastle-under-Lyme, ST5 5BG, UK*

³⁸*School of Mathematical and Physical Sciences, Macquarie University, Sydney, NSW 2109, Australia*

ABSTRACT

Planetary nebulae are sites where ejected stellar material evolves into complex molecules, but the precise physical conditions and chemical routes that govern these processes are unclear. The presence of abundant carbon-rich molecules in O-rich environments poses particular challenges. Here we report the first detection of methyl cation (CH₃⁺) in any planetary nebula, observed in the O-rich nebula NGC 6302 using JWST MIRI/MRS

observations. CH_3^+ is a key driver of organic chemistry in UV-irradiated environments. Spatially resolved observations reveal that CH_3^+ is co-located with ^{12}CO , H_2 , **H II**, HCO^+ , and Polycyclic aromatic hydrocarbons (PAHs). LTE modelling of the CH_3^+ emission yields excitation temperatures of 500-800K in the inner bubble and torus, rising to 1000-2000K in the outer bubble of NGC 6302, with column densities ranging from $\sim 10^{11}$ to 10^{13} cm^{-2} . This detection demonstrates that hydrocarbon radical chemistry must be incorporated into planetary nebulae chemical models. Further near-IR observations are crucial to map different chemical networks operating in these environments.

Keywords: Astrochemistry (75), Circumstellar Gas (238), Planetary nebulae (1249), Small molecules (2267)

1. INTRODUCTION

As of August 2025, more than 330 molecular species have been identified in interstellar and circumstellar environments. A substantial subset of this inventory originates in the circumstellar envelopes of evolved stars, including stars on the asymptotic giant branch (AGB), post-AGB stars, and planetary nebulae (singular: PN; plural: PNe; [B. A. McGuire 2022](#); [M. Araki 2025](#)). Elucidating how these molecules form and evolve as local physical conditions change is essential for constraining a wide range of astrochemical and astrophysical processes such as star- and planet formation and the chemical enrichment of galaxies, among others (see [A. G. G. M. Tielens 2013](#), for a review).

During the AGB phase, low- to intermediate-mass ($\sim 1-8 M_\odot$) stars undergo severe mass-loss with mass-loss rates ranging from 10^{-8} to $10^{-4} M_\odot \text{ yr}^{-1}$ ([S. Höfner & H. Olofsson 2018](#)). These AGB outflows result in the formation of a circumstellar envelope (CSE). As the stellar gas expands radially away from the stellar atmosphere, it cools down, resulting in the formation of molecules and dust. The infrared (IR) spectra of AGB stars indeed show the presence of a rich variety of molecules. More than 90 molecules have been detected in the CSE around carbon-rich stars, and about 27 around oxygen-rich stars (see [M. Agúndez et al. 2014](#); [L. Decin et al. 2018](#); [M. Agúndez 2022](#); [B. A. McGuire 2022](#), and references there in). Note that the molecular species detected in the CSE of AGB stars are mainly simple molecular species, such as CO , C_2H_2 , HCN , CO_2 , H_2O , etc. Eventually, the star progresses through the post-AGB phase and the effective temperature of the star, T_{eff} , increases rapidly with decreasing stellar radii. As $T_{\text{eff}} \gtrsim 20,000\text{K}$, UV radiation from the star ionizes the hydrogen in the previously ejected material and a PN is formed ([K. B. Kwitter & R. B. C. Henry 2022](#)). UV photons from the star can also lead to dissociation of molecules in the CSE, and not all molecules survive the transition from the AGB to the PN phase. In fact, a sharp drop is seen in the molecular inventory of PN compared to that of the AGB phase ([M. Agúndez 2022](#)). Interestingly, spectral features of larger and more complex molecules like Polycyclic Aromatic Hydrocarbons (PAHs) and fullerenes, such as C_{60} , C_{70} , begin to appear in the post-AGB and PN

phase ([M. Matsuura et al. 2005, 2014](#); [N. L. J. Cox et al. 2016](#); [J. Cami et al. 2010](#); [Y. Zhang & S. Kwok 2011](#)).

A key concept in the chemistry of evolved stars is that the chemistry in the AGB outflows depends primarily on the C/O ratio of the stellar photosphere. All stars start their lives as oxygen-rich ($\text{C/O} < 1$) stars, but third dredge-up events in low- and intermediate-mass stars ($\sim 1.5-4 M_\odot$; [D. A. García-Hernández et al. 2013](#)) elevate this C/O ratio above unity late in the AGB phase, converting the envelope to carbon-rich. After H_2 , the next molecule to form in the stellar photosphere is carbon monoxide (CO), which is a highly stable molecule. CO locks up all the free carbon or oxygen atoms – depending on which species is most abundant – leaving the remaining carbon or oxygen to drive further chemistry. Oxygen-rich stellar envelopes thus exhibit the presence of oxides (such as H_2O , SO , AlOH , etc.), and crystalline silicates ([R. J. Sylvester et al. 1999](#); [J. Cami 2002](#); [T. Posch et al. 2002](#); [H. Kim et al. 2010](#); [L. Decin et al. 2010](#); [E. De Beck et al. 2013](#); [L. Decin et al. 2018](#)) while carbon-rich stellar envelopes are characterized by the presence of hydrocarbons, PAHs, fullerenes and amorphous dust ([T. I. Hasegawa & S. Kwok 2001](#); [J. Cami et al. 2010](#); [M. Agúndez et al. 2014](#)).

However, [A. A. Zijlstra et al. \(1991\)](#) presented the first evidence of mixed or dual chemistry in a PN - where the spectrum of a young PN (IRAS 07027-7934) showed the simultaneous presence of strong PAH emission as well as 1.6 GHz OH maser line emission. Using observations by the Infrared Space Observatory, more cases of dual chemistry in PNe were reported by [L. B. F. M. Waters et al. \(1998a,b\)](#) and [M. Cohen et al. \(2002\)](#). Furthermore, using Spitzer observations, [J. V. Perea-Calderón et al. \(2009\)](#) showed that out of 26 PNe observed towards the galactic bulge, 21 showed signatures of dual chemistry. A larger survey by [L. Stanghellini et al. \(2012\)](#) showed that 46% of the bulge PNe and 24% of the galactic PNe exhibit dual chemistry. It is not clear whether this dual-chemistry phenomenon arises on the AGB or emerges later as a result of processing during the PN phase. Consequently, our knowledge and understanding of the chemical pathways in late stages of stellar evolution, from the AGB phase to PN, is incomplete. It is important to explore how the inventory of molecules is affected by the dual

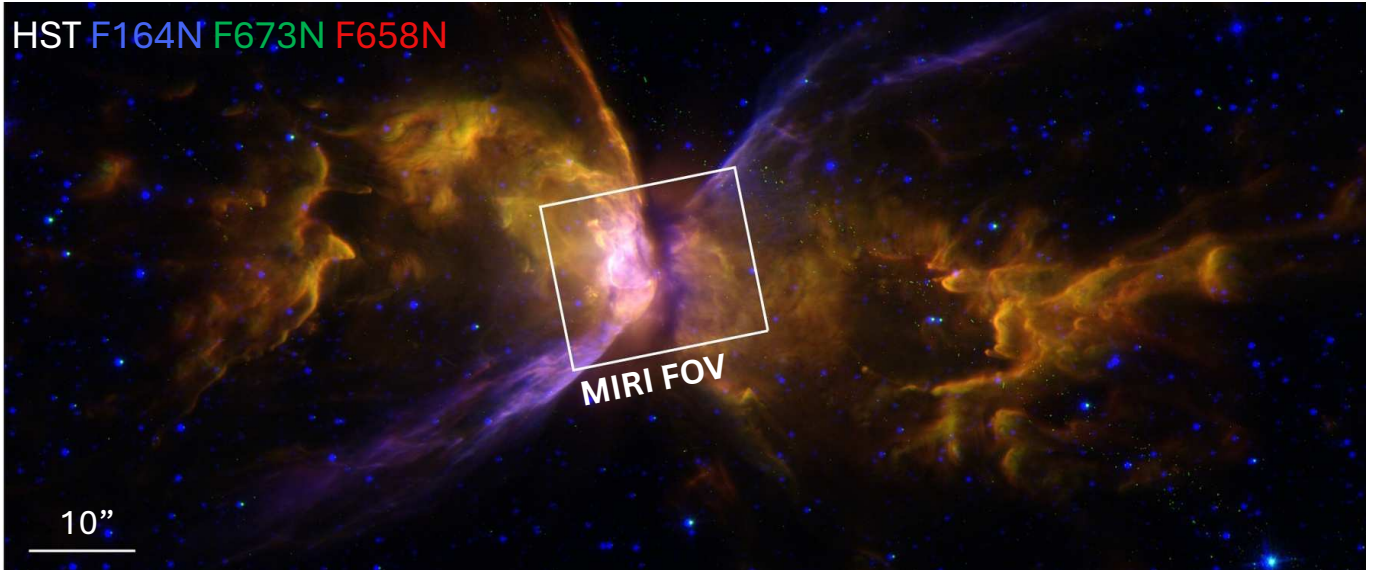


Figure 1. Three-colour composite HST image of NGC 6302, created by Matsuura et al. (2025, MNRAS, submitted) utilizing images from J. H. Kastner et al. (2022) and B. Balick et al. (2023). This image presents a colour overlay of WFC3 observations of NGC 6302, featuring F164N filter in blue, which traces $[\text{Fe II}]$ emission, F656N filter in green, which traces $\text{H}\alpha$ emission, and F658N in red, which traces $[\text{N II}]$ emission. The white box at the center represents the MIRI field-of-view for observations described in Sect. 2.

141 chemistry, and eventually, what chemical reactions can occur
 142 which are not accounted for by strictly C-rich or O-rich
 143 chemical pathways. This can potentially provide clues to the
 144 formation of other chemical species; for example, the forma-
 145 tion of large carbonaceous aromatic molecules like PAHs in
 146 an O-rich environment.

147 In this paper, we report the unambiguous detection of the
 148 methyl cation (CH_3^+) in the NGC 6302, a small but important
 149 carbonaceous species in what is very clearly an O-rich envi-
 150 ronment ($\text{C}/\text{O} \approx 0.5$, N. J. Wright et al. 2011). While CH_3^+
 151 has long been considered a key species for carbon chem-
 152 istry in interstellar environments (J. H. Black & A. Dalgarno
 153 1977; D. Smith 1992; A. Sternberg & A. Dalgarno 1995; E.
 154 Herbst 2021), its first detection outside the Solar System is
 155 a much more recent milestone. CH_3^+ was first detected via
 156 JWST/MIRI observations of the irradiated proplyd d203-506
 157 in the Orion Bar by O. Berné et al. (2023). The species is
 158 also present at much larger scales in the Orion Bar PDR (M.
 159 Zannese et al. 2025) and in the disk of a T-Tauri star (T. Hen-
 160 ning et al. 2024). Our detection in NGC 6302 is the first time
 161 this species has been detected in a planetary nebula.

2. OBSERVATIONS AND DATA REDUCTION

162 We use the JWST MIRI/MRS observations of NGC 6302,
 163 which were obtained as part of the JWST GO Cycle 1 pro-
 164 gram 1742. The pointing was centred on the central region
 165 of NGC 6302 at R.A. = $17^{\text{h}}:13^{\text{m}}:44.3938^{\text{s}}$, Dec. = $-$
 166 $37^{\circ}:06':12.36$ (J2000). The observations were taken with the
 167 MIRI Medium Resolution Spectrometer (MRS) with Integral
 168 Field Unit (IFU). The data was obtained for the entire MIRI
 169 wavelength range, which is 4.9 to $27.9 \mu\text{m}$ spread across 4

171 channels (M. Wells et al. 2015; I. Argyriou et al. 2023). A
 172 mosaic of 5×5 tiles was used to cover the central part of
 173 NGC 6302, which includes the central star, the torus, and the
 174 bright ionized line emitting region at the innermost region of
 175 the bipolar outflow (see fig. 1). Four-point dithering was used
 176 to optimize spatial and spectral sampling throughout the field
 177 of view.

178 We used the development version of v1.14.0
 179 JWST Calibration Pipeline with versions 11.17.16 and
 180 “jwst_1202.pmap” of the Calibration Reference Data Sys-
 181 tem (CRDS) and CRDS context, respectively. All level 1b
 182 files were processed through Detector1Pipeline to obtain
 183 level 2a (rate) images. The background exposures were
 184 subtracted from the science exposures to get background-
 185 subtracted level 2a files. These were then processed through
 186 Spec2Pipeline (with residual.fringe step tuned on),
 187 followed by Spec3Pipeline to produce spectral cube mo-
 188 saics of NGC 6302. For details on the observations and data
 189 reduction, we refer to Matsuura et al., 2025, MNRAS, in
 190 press.

3. THE PLANETARY NEBULA NGC 6302

191 NGC 6302 is a butterfly-shaped planetary nebula, $1.03 \pm$
 192 0.27 kpc away from Earth (S. Gómez-Gordillo et al. 2020),
 193 towards the constellation Scorpius. N. J. Wright et al. (2011)
 194 constructed a 3D photoionization model of NGC 6302 and
 195 constrained the properties of its central star. They derived
 196 an effective temperature of 220,000K, which explains the
 197 presence of highly ionized species such as $[\text{Mg VII}]$ and
 198 $[\text{Si VII}]$. The same study yields a stellar mass of $0.73\text{--}0.82$
 199 M_{\odot} (with an initial mass of about $5.5 M_{\odot}$), and a luminosity
 200

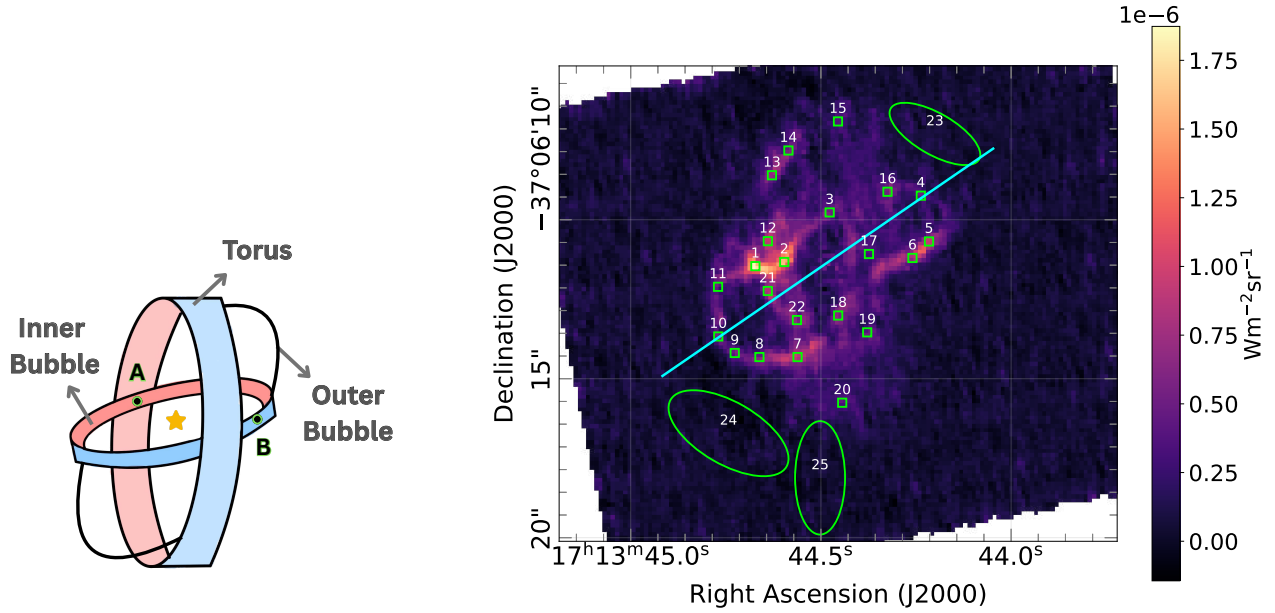


Figure 2. *Left panel:* The cartoon provides a schematic representation of the central region of NGC 6302. Blue and red colours indicate the blueshift and redshift caused by the expansion of the torus and inner bubble from the Earth’s perspective. The schematic is based on the results of [M. Santander-García et al. \(2017\)](#) and [Matsuura et al., 2025, MNRAS, in press](#). The line-of-sight motion of the outer bubble is not constrained and thus is represented by arcs. Points A and B are two bright spots on CH_3^+ integrated surface brightness map. *Right panel:* Integrated surface brightness map of CH_3^+ , obtained by integrating the surface brightness over the $7.13\text{--}7.2\ \mu\text{m}$ wavelength range at each pixel. The green boxes and ellipses represent the 25 apertures where we analyzed the CH_3^+ emission in more detail. Aperture 1-22 are 2×2 pixels, which is $0''.26 \times 0''.26$. Apertures 23-25 are larger elliptical regions with areas of $3''.22^2$, $6''.52^2$, and $4''.36^2$, respectively. The cyan line represents the cut used for making Fig. 9.

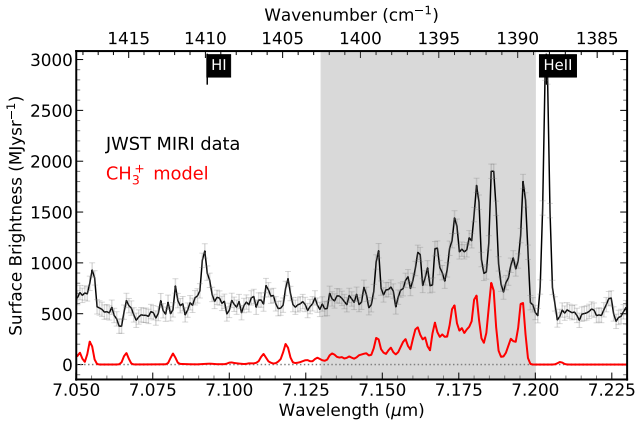


Figure 3. The continuum-subtracted JWST/MIRI spectrum of NGC 6302 at aperture 1 shown in Fig 2 (black, offset vertically for clarity) compared to a CH_3^+ model (red) by [P. B. Changala et al. \(2023\)](#) at excitation temperature of 600 K. The H I recombination line at $7.0928\ \mu\text{m}$ and the He II line at $7.2036\ \mu\text{m}$ are labelled at the top.

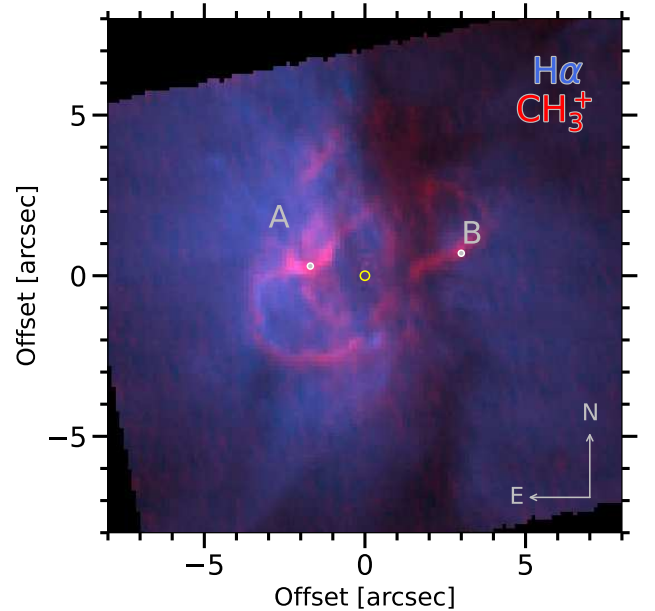


Figure 4. The image represents a colour overlay of HST/WFC3 observations featuring filter F656N in blue ([J. H. Kastner et al. 2022](#)) which traces emission from $\text{H}\alpha$, and CH_3^+ map in red.

of $14,300 L_{\odot}$. NGC 6302 is O-rich with $\text{C/O} \approx 0.5$ ([N. J. Wright et al. 2011](#)).

Optical images (see Fig. 1) reveal two lobes of luminous gas, shaped like the wings of a butterfly. Its bipolar lobes (which stretch as far as 2.1 pc) are exceptionally bright

and exhibit a rich variety of emission lines, from the far-ultraviolet to the mid-infrared (S. Casassus et al. 2000; W. A. Feibelman 2001). NGC 6302 is known for exhibiting one of the most complex morphologies seen in PNe. Optical observations (HST/WFC3) also reveal that the two lobes, which are oriented east-west, show small-scale structures such as clumps, tails, knots, and filaments, which seem to be in azimuthally organized zones. [Fe II] emission reveals jets coming out from the central region in south-east and north-west directions, forming an S-shape (J. H. Kastner et al. 2022; B. Balick et al. 2023).

The central region of NGC 6302 comprises three major morphological structures: the *torus* (sometimes referred to as the "central dark lane" or "main ring" in previous studies), the *inner bubble* (sometimes referred to as the "inner ring" in previous studies) and the *outer bubble*. A schematic presentation of these morphological structures is provided in Fig. 2.

The torus is massive and dense with a total (dust and gas) mass of 0.8–3 M_{\odot} and size of 5700 AU (Matsuura et al., 2025, MNRAS, in press). It is the primary reservoir of dust in NGC 6302. These authors point out that the torus is distorted or warped at the edges and is filled with crystalline silicates and other dust grains. In optical observations, the torus appears as a central dark lane that bisects the two lobes and runs nearly north-south, orthogonal to the lobes (see Fig. 1). That dark lane is the front part of the torus that surrounds the central star, obscuring the star in the visible and near-IR (J. H. Kastner et al. 2022). ALMA ¹²CO J=3–2 maps reveal the torus in great detail and provide kinematic information. The torus is non-Keplerian and is radially expanding at a velocity of 8 km s⁻¹. The kinematical age of the torus is estimated to be ~5000–7500 years (N. Peretto et al. 2007; M. Santander-García et al. 2017).

The inner bubble has been observed at optical, mid-IR and sub-mm wavelengths as it is traced by emission of several species such as H II, H₂, ¹²CO, HCO⁺, PAHs, etc (M. Santander-García et al. (2017); J. H. Kastner et al. (2022), Matsuura et al., 2025, MNRAS, in press, Moraga Baez et al., 2025, under review, Clark et al., in prep). The inner bubble, which runs east-west, is peanut-shaped and is pinched where it intersects with the previously ejected torus (Matsuura et al., 2025, MNRAS, in press). The inner bubble is inclined approximately 60° relative to the torus, and is expanding with a velocity of 11 km s⁻¹. It is much younger than the torus, with a kinematical age of ~2200 years (M. Santander-García et al. 2017). B. Balick et al. (2023) describe the sequence of several episodes of ejection from the center of the NGC 6302 in detail.

While the torus and the inner bubble have been detected in optical and sub-mm observations before, JWST MIRI observations by Matsuura et al., 2025, MNRAS, in press revealed two arcs outside the inner bubble, towards the southeast and

northwest, inclined with respect to both the inner bubble and the torus (see Fig. 2). Those arcs constitute the outer bubble, which is bright in H₂ and PAH emission. (Matsuura et al., 2025, MNRAS, in press, Clark et al., in prep).

4. CH₃⁺ EMISSION IN NGC 6302

The JWST/MIRI observations of the central region of NGC 6302 reveal the characteristic CH₃⁺ emission band in the 7.13–7.20 μm range (see Fig. 3) and show that the emission is spatially extended and resolved across distinct regions.

4.1. The spatial distribution of CH₃⁺

To reveal the spatial distribution of CH₃⁺, we integrated the surface brightness over the wavelength range 7.13–7.20 μm after continuum subtraction for each spatial pixel in the MIRI field of view. We restricted the integration to these wavelengths to avoid contributions from other species. An example of the adopted continuum is shown in Appendix A, and the resulting map of the integrated surface brightness is shown in Fig. 2. The map shows bright CH₃⁺ emission along the inner bubble's edge (east-west orientation) and the torus (north-south orientation). Although not visible on the map, we found that CH₃⁺ is also present in the outer bubble (see below), but the column densities are too low to be visible in the integrated surface brightness map. To guide the reader and facilitate spatial comparison, we compared the CH₃⁺ map to the HST/WFC3 image (through the F656N filter; see J. H. Kastner et al. 2022), which traces Hα emission, in Fig. 4. Note that the CH₃⁺ emission along the torus overlaps with what appears as a central dark lane in the Hα observations.

To better understand what drives the CH₃⁺ emission, we investigate its spectroscopic characteristics and spatial variations using defined apertures rather than individual pixels to achieve better signal-to-noise (S/N) ratios. We selected 25 apertures to sample all distinct regions with CH₃⁺ emission along the torus, inner bubble, and outer bubble (see Fig. 2). Apertures 1–22 use 2×2 pixel areas, each covering 0''.26×0''.26 given the 0''.13 pixel scale in channel 1c. Apertures 23–25 are larger elliptical regions (with areas 3''.22², 6''.52², and 4''.36² respectively) to achieve adequate S/N for the weaker CH₃⁺ emission in the outer bubble. These apertures were positioned to cover the outer bubble arc structure as guided by the H₂ map (see Appendix B). The aperture distribution is as follows: apertures 1–2 cover the intersection of the inner bubble and torus; apertures 3–6 and 7–11 trace the west and east edges of the inner bubble, respectively; aperture 12 lies north of the intersection point; apertures 13–15 trace the north rear side of the torus; apertures 16–20 and 21–22 trace the front and rear edges of the torus, respectively; and apertures 23–25 sample the outer bubble's northwest arc and south-southwest region.

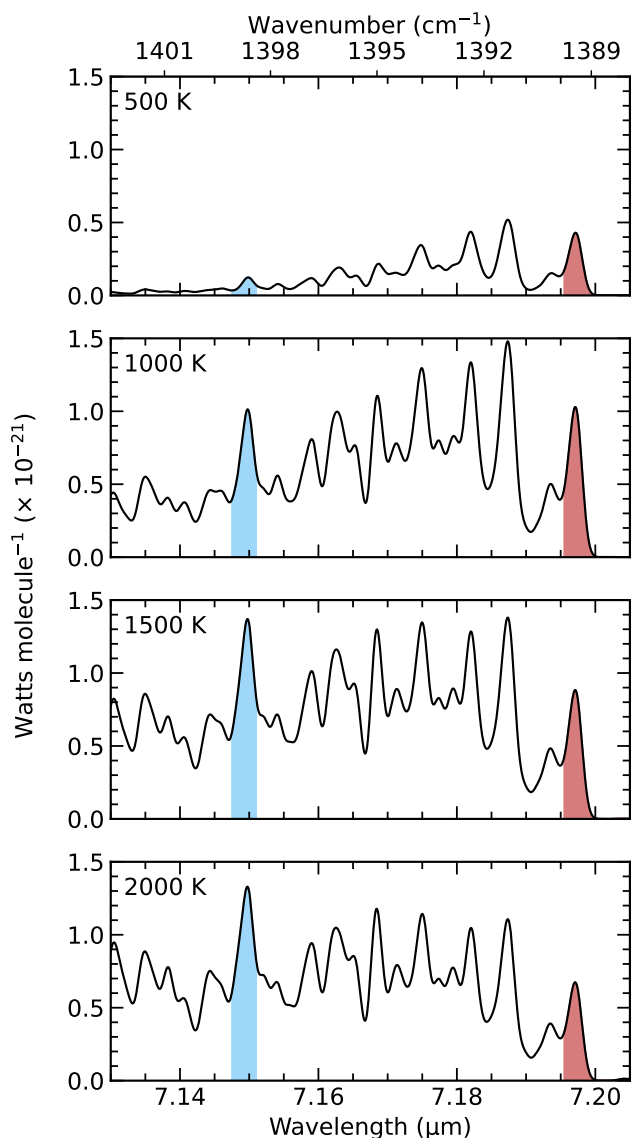


Figure 5. Model spectra of CH_3^+ at 500, 1000, 1500 and 2000 K. Bands at 7.15 and 7.2 μm are highlighted in blue and red, respectively.

4.2. Spectroscopic analysis of the CH_3^+ emission

CH_3^+ has a trigonal planar geometry (D_{3h} point group) and it lacks a permanent dipole moment. Because of that, it cannot be observed at radio wavelengths. However, it can be detected via ro-vibrational transitions at infrared wavelengths. CH_3^+ has symmetric (ν_1) and degenerate asymmetric (ν_3) stretching modes at around 3 μm ($\sim 3100 \text{ cm}^{-1}$), an out-of-plane umbrella bending mode (ν_2) and a degenerate in-plane (ν_4) bending mode at 7.2 μm ($\sim 1400 \text{ cm}^{-1}$; J. Meisner et al. 2019; P. B. Changala et al. 2023). Coriolis interactions between the ν_2 and ν_4 bands (also referred to as ν_2/ν_4 dyad) result in a characteristic pattern of ro-vibrational lines that occur in the 7.15–7.2 μm range.

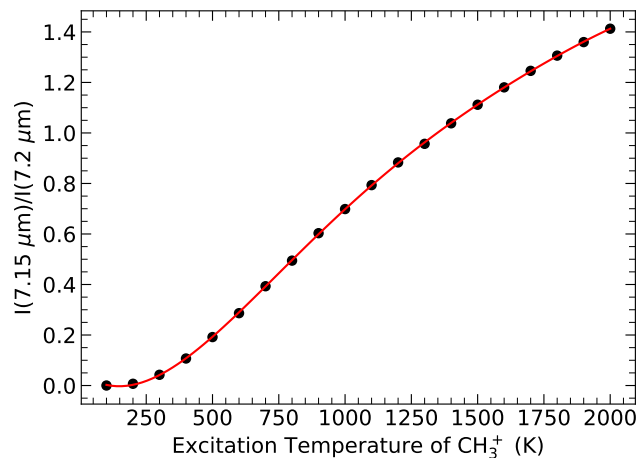


Figure 6. Intensity ratio $I(7.15 \mu\text{m})/I(7.2 \mu\text{m})$ as a function of excitation temperature of CH_3^+ . Black points represent the $I(7.15 \mu\text{m})/I(7.2 \mu\text{m})$ found in the model spectra for a given excitation temperature. A five-degree polynomial fit to those points is represented by the red curve. The polynomial is given by Eq. 1

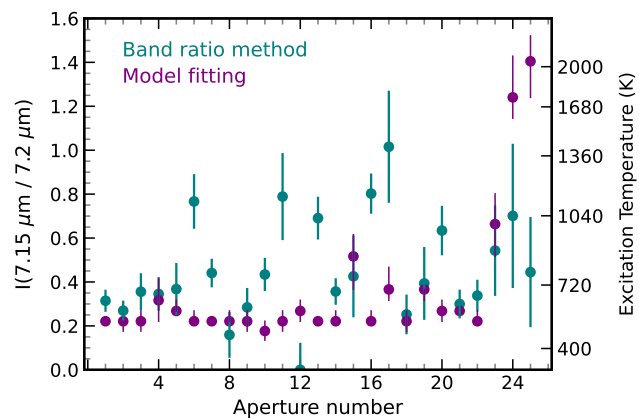


Figure 7. CH_3^+ excitation temperature derived for the 25 selected apertures. Teal points represent the $I(7.15 \mu\text{m})/I(7.2 \mu\text{m})$ band found in the observed extracted spectra. The corresponding temperatures (as described by Eq. 1) are shown on the y-axis on the right. Purple points represent the best-fit temperature derived from fitting models to the observations.

We compare the observations to the CH_3^+ model developed by P. B. Changala et al. (2023) using the latest and most detailed rovibrational assignments of the CH_3^+ feature based on theoretical and experimental studies. They performed detailed quantum mechanical calculations to derive spectroscopic constants (for the ν_2/ν_4 dyad) such as rotational constants, coriolis coupling constant, centrifugal distortion constants, etc., in the vibronic ground state of CH_3^+ . These constants were then validated by two different experimental methods. We use the PGOPHER (a general-purpose software for simulating electronic, vibrational and rotational spectra; C. M. Western 2017) file provided by (P. B. Changala et al.

2023) to compute the CH₃⁺ model spectrum that can be compared to the observations at 7.2 μm at JWST’s resolution. Note that the models assume a thermal distribution across rotational levels at ν=1 level. We used PGOPHER to calculate CH₃⁺ models spanning the temperature range from 100 K to 3000 K in steps of 50 K, where the spectrum is convolved with a Gaussian adopting a full width half maximum (FWHM) of 0.37 cm⁻¹, corresponding to the JWST resolving power of R = 3600 at 7.2 μm (channel 1c; see I. Argyriou et al. 2023). We exported the models in the units of Watts per molecule.

Fig. 5 shows how the Q-branch of the CH₃⁺ model spectrum changes as a function of excitation temperature. At JWST’s resolution, overlapping Q-branch lines cause a bump to appear. Note that the strength of different bands peaks at different temperatures based on the rotational levels of the transitions involved. For example, the strength of the 7.15 μm band is lower than that of the 7.2 μm band at lower temperatures. However, at temperatures above 1000K, the opposite is true. The intensity ratio of the 7.15 μm band (shaded blue in Fig. 5) to the 7.20 μm line (shaded red) is very small (<1) at low temperatures, ~1 at about 1300 K and much higher (>1) at high temperatures. This band ratio is thus a sensitive diagnostic of the CH₃⁺ excitation temperature.

We will use this as a first estimate to determine the excitation temperature in the selected apertures, a diagnostic first used by M. Zannese et al. (2025) for the analysis of CH₃⁺ emission in Orion Bar PDR. We fit a gaussian with a linear baseline to the 7.15 μm (7.147 - 7.151 μm) band and 7.20 μm (7.195 - 7.199 μm) band, for both models and observations. The ratio of I(7.15 μm)/I(7.2 μm) derived from the model spectra versus excitation temperature is shown in Fig. 6, which exhibits the behaviour described above. This ratio should change gradually as a function of temperature, and to obtain a continuous form of this function, we fitted a polynomial to the data points. We found that a fifth-order polynomial fits the individual points well (see Fig. 6) using the following coefficients:

$$T(x) = 1883x^5 - 7260x^4 + 10640x^3 - 6956x^2 + 2941x + 159.6 \quad (1)$$

where x is the band ratio. We can then use this polynomial to determine the excitation temperature using measured band ratios in the observational spectra. For each of the 25 apertures, we applied the same fitting procedure to the 7.15 μm and 7.20 μm bands as done for the models. These fits are shown in Appendix C, and the intensity and uncertainties on the bands and the band ratios are listed in Table 1. The uncertainties in the observations determine uncertainties in the intensity. The teal points in Fig. 7 show the band ratio and temperatures derived for each aperture based on Eq. 1. All apertures exhibit excitation temperatures of 500–1000 K (band

ratios of 0.15–0.80). While the reported uncertainties primarily reflect random errors, systematic effects—especially those introduced by the linear baseline fit—are harder to quantify and could artificially increase or decrease the band ratios in certain apertures.

We can also determine the excitation temperatures by directly fitting model spectra to the continuum-subtracted spectra, with the temperature and column density of CH₃⁺ as free parameters. We used the continuum-subtracted flux (in W m⁻² μm⁻¹) in the range of 7.13–7.199 μm to fit models to observations. We used the `lmfit` (M. Newville et al. 2014) python package, adopting a Levenberg-Marquardt algorithm to determine temperatures and column densities; the excitation temperatures, however, were constrained on a grid with values between 100 K and 3000 K in steps of 50 K. We also allowed for small wavelength shifts (~ ±0.0015 μm) during fitting to account for radial velocity corrections. Appendix D shows the resulting best fits for all 25 apertures, and the resulting best fit parameters are listed in Table 1. Parameter uncertainties presented in Table 1 denote 1σ confidence intervals, obtained from the projections of the Δχ² = 1 contour on the χ² surface. The models generally reproduce the observations extremely well, leaving only very small residuals in this wavelength range. We find that the excitation temperature is in the range of 500–800K for apertures 1-22 and temperature 1000-2000K for apertures 23-25; these are represented by purple points in Fig 7.

Although no clear patterns exist in excitation temperature variations across the inner bubble and torus, the outer bubble exhibits significantly higher temperatures (1000–2000 K) compared to 500–800 K elsewhere. The column densities (Table 1) are typically a few times 10¹² cm⁻², ranging about two orders of magnitude from the lowest (aperture 23) to highest (aperture 1) values. The highest column density is seen where the inner bubble runs into the rear side of the torus. These column densities are however, not an accurate representation of the total CH₃⁺ column density: as was pointed out by O. Berné et al. (2023) and M. Zannese et al. (2025) since the CH₃⁺ emission originates from chemical pumping and consequently, the excitation of the vibrational levels is far from LTE.

5. DISCUSSION

5.1. Formation of CH₃⁺ in NGC 6302

The detection of CH₃⁺ in NGC 6302 was surprising at first because this is an O-rich PN where most carbon is locked up in CO, making carbon chemistry unlikely. However, intense UV radiation from the central star fundamentally changes this scenario by providing two key ingredients required for the formation of CH₃⁺: C⁺ ions and vibrationally excited H₂. C⁺ reacts with the vibrationally excited H₂ to form CH⁺, followed by two successive exothermic hydrogen abstraction

Table 1. The excitation temperature, column density and wavelength shift for each of the 25 apertures from Fig. 2.

Aperture	$I_{7.15} \pm \sigma$ [10^{-1}]	$I_{7.20} \pm \sigma$ [10^{-1}]	Ratio $\pm \sigma$ [10^{-1}]	T^a [K]	T^b [K]	$N \pm \sigma_N$ [10^{12} cm^{-2}]	wavelength shift [$10^{-3} \mu\text{m}$]
1	8.3 ± 1.3	26.4 ± 1.3	3.1 ± 0.5	660^{+40}_{-50}	550^{+0}_{-0}	13.3 ± 0.2	-1.02 ± 0.03
2	7.2 ± 1.2	26.6 ± 1.2	2.7 ± 0.5	620^{+40}_{-50}	550^{+0}_{-50}	11.4 ± 0.2	-0.97 ± 0.04
3	4.0 ± 0.9	11.2 ± 0.9	3.6 ± 0.8	700^{+70}_{-80}	550^{+50}_{-50}	3.8 ± 0.2	-0.84 ± 0.09
4	5.5 ± 1.1	16.0 ± 1.1	3.5 ± 0.8	690^{+70}_{-70}	650^{+100}_{-100}	2.0 ± 0.1	-1.17 ± 0.1
5	4.3 ± 1.3	11.8 ± 1.3	3.7 ± 1.2	710^{+100}_{-110}	600^{+50}_{-0}	5.4 ± 0.1	-1.18 ± 0.05
6	8.9 ± 1.2	11.7 ± 1.2	7.7 ± 1.2	1110^{+150}_{-140}	550^{+50}_{-0}	5.8 ± 0.2	-1.19 ± 0.06
7	6.7 ± 0.9	15.1 ± 0.9	4.4 ± 0.7	770^{+60}_{-60}	550^{+0}_{-0}	6.9 ± 0.1	-1.16 ± 0.04
8	1.4 ± 0.9	8.6 ± 0.9	1.6 ± 1.0	490^{+120}_{-190}	550^{+50}_{-0}	4.5 ± 0.1	-1.19 ± 0.06
9	3.5 ± 1.0	12.3 ± 1.0	2.8 ± 0.9	630^{+80}_{-100}	550^{+50}_{-50}	4.1 ± 0.2	-1.12 ± 0.1
10	7.7 ± 1.2	17.7 ± 1.2	4.3 ± 0.8	770^{+70}_{-70}	500^{+50}_{-50}	5.8 ± 0.2	-1.12 ± 0.06
11	4.8 ± 1.0	6.1 ± 1.0	7.9 ± 2.0	1140^{+250}_{-220}	550^{+50}_{-50}	3.3 ± 0.2	-0.9 ± 0.1
12	0.0 ± 1.7	13.7 ± 1.7	0.0 ± 1.2	160^{+270}_{-490}	600^{+50}_{-50}	5.7 ± 0.1	-1.01 ± 0.05
13	8.0 ± 0.9	11.6 ± 0.9	6.9 ± 1.0	1020^{+110}_{-110}	550^{+0}_{-0}	5.4 ± 0.1	-0.95 ± 0.05
14	3.7 ± 0.6	10.4 ± 0.6	3.6 ± 0.6	700^{+50}_{-50}	550^{+50}_{-0}	4.5 ± 0.1	-1.1 ± 0.07
15	2.3 ± 0.9	5.4 ± 0.9	4.3 ± 1.9	760^{+180}_{-170}	850^{+100}_{-150}	1.0 ± 0.1	-0.74 ± 0.13
16	10.1 ± 0.9	12.5 ± 0.9	8.0 ± 0.9	1150^{+120}_{-110}	550^{+50}_{-0}	4.6 ± 0.2	-1.14 ± 0.07
17	4.2 ± 0.7	4.1 ± 0.7	10.2 ± 2.6	1430^{+380}_{-320}	700^{+100}_{-50}	1.4 ± 0.1	-1.13 ± 0.12
18	3.4 ± 1.2	13.6 ± 1.2	2.5 ± 0.9	600^{+90}_{-110}	550^{+50}_{-50}	4.7 ± 0.2	-1.25 ± 0.07
19	1.7 ± 0.7	4.2 ± 0.7	3.9 ± 1.7	730^{+150}_{-160}	700^{+0}_{-50}	1.8 ± 0.1	-1.34 ± 0.09
20	5.4 ± 0.8	8.6 ± 0.8	6.3 ± 1.1	960^{+130}_{-110}	600^{+50}_{-50}	2.2 ± 0.1	-1.16 ± 0.08
21	3.2 ± 0.7	10.8 ± 0.7	3.0 ± 0.7	650^{+60}_{-70}	600^{+0}_{-0}	4.8 ± 0.1	-0.81 ± 0.05
22	4.6 ± 0.9	13.5 ± 0.9	3.4 ± 0.7	680^{+60}_{-70}	550^{+50}_{-0}	4.8 ± 0.1	-0.85 ± 0.05
23	0.7 ± 0.2	1.4 ± 0.2	5.4 ± 2.1	870^{+220}_{-180}	1000^{+150}_{-150}	0.2 ± 0.0	-0.96 ± 0.11
24	1.0 ± 0.4	1.4 ± 0.4	7.0 ± 3.3	1030^{+410}_{-320}	1750^{+350}_{-150}	0.4 ± 0.0	-1.05 ± 0.1
25	0.9 ± 0.5	2.0 ± 0.5	4.4 ± 2.5	780^{+250}_{-240}	2050^{+500}_{-300}	0.4 ± 0.0	-1.05 ± 0.11

^aBand ratio method^bModel fitting

reactions to produce CH_3^+ (O. Berné et al. 2023; M. Zan-
 nese et al. 2025). The UV radiation plays a crucial role be-
 cause it dissociates and photoionizes CO, thereby providing
 C^+ . Moreover, in such environments, the energy barrier of
 the CH^+ step ($\approx 0.40 \text{ eV}$ or $\sim 4640 \text{ K}$) is overcome by FUV-
 pumped H_2 , which leaves H_2 in a vibrationally excited state
 (M. Agúndez et al. 2010; Z. Nagy et al. 2013; B. Godard &
 J. Cernicharo 2013). CH^+ and CH_3^+ form in a vibrationally
 excited state and then relax radiatively. This excitation mech-
 anism is called chemical (formation) pumping, and the ob-
 served emission thus traces the newly formed CH^+ and CH_3^+ .

Our observations confirm this formation pathway in
 NGC 6302 through spatial comparison of ^{12}CO , H_2 and CH_3^+ .
 Fig. 8 shows that ^{12}CO and H_2 are indeed present where CH_3^+
 emission is detected i.e. where CH_3^+ is formed. CH_3^+ and
 ^{12}CO are also present in the outer bubble, but as mentioned

above, their column densities are too low to be visible in the
 integrated surface brightness map. Since the vibrationally ex-
 cited H_2 lines detected with JWST/MIRI data have very low
 S/N, their spatial distribution has large uncertainties for com-
 parison with CH_3^+ distribution. We therefore use the H_2 0-0
 S(5) line (at $6.908 \mu\text{m}$) as a tracer for the H_2 distribution.

Fig. 9 shows the normalized surface brightness profile of
 these species along the cut indicated in Fig. 2, zoomed in to
 show the east and west edges of the bubble. On the east edge,
 CH_3^+ , ^{12}CO and H_2 show peaks in the surface brightness pro-
 files at the same distance from the star, with CH_3^+ and H_2
 having very similar profiles. The west edge shows a very dif-
 ferent distribution, likely because of projection effects. No-
 tably, CH_3^+ exhibits the sharpest rise and fall at the inner bub-
 ble edge compared to other species, including H_2 . This could
 indicate where FUV-pumped H_2 ($v>0$) is available; however,

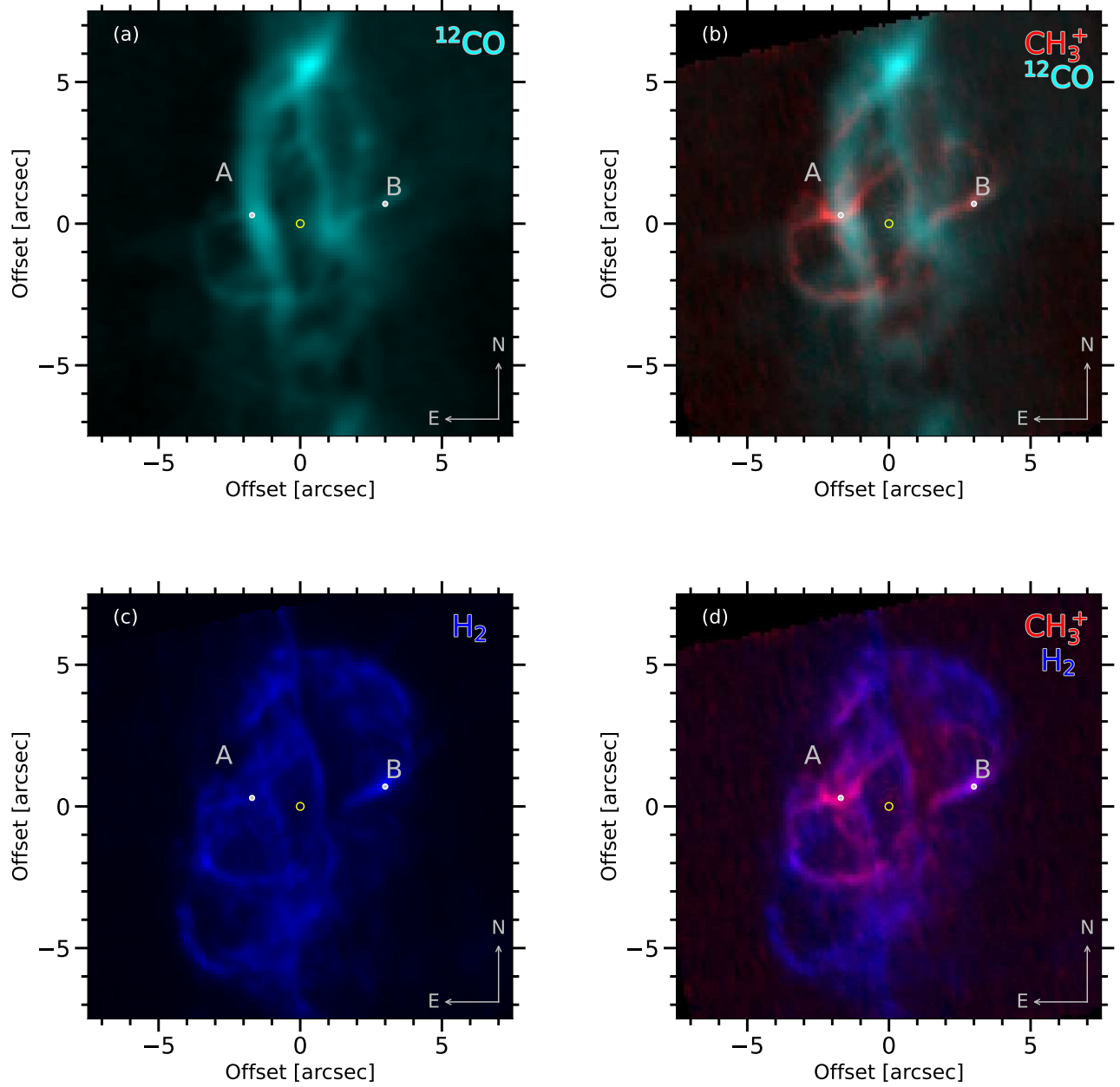


Figure 8. Comparison of the integrated surface brightness maps of CH_3^+ , H_2 and ^{12}CO . (a) ^{12}CO (2–1, 230GHz, by Moraga Baez et al., 2025, under review). (b) Two colour composite image: CH_3^+ (red) and ^{12}CO (cyan). (c) H_2 0-0 S5 at $6.908 \mu\text{m}$ (d) Two colour composite image: CH_3^+ (red) and ^{12}CO (cyan). Locations marked by A and B represent the two bright spots on CH_3^+ map. The maps are centred at the central star (R.A. = $17^{\text{h}}:13^{\text{m}}:44.488 \pm 0.004^{\text{s}}$, Dec. = $-37^{\circ}:06':11.76 \pm 0.03'$) whose position is indicated by the yellow circle at the center.

465 NIRSpc observations of vibrationally excited H_2 lines are
 466 needed for confirmation. Alternatively, this may reflect the
 467 influence of fast winds or energetic shocks that formed the
 468 inner bubble (Matsuura et al., 2025, MNRAS, in press), con-
 469 fining CH_3^+ formation to a narrow region along the edge.

470 5.2. Spatial variations in CH_3^+ emission

471 CH_3^+ emission shows significant spatial variations in col-
 472 umn density across NGC 6302. The most prominent features
 473 are two bright spots, Points A and B, which exhibit simi-
 474 lar temperatures to other regions but significantly higher col-
 475 umn densities (See Fig. 2). This enhancement occurs where
 476 the inner bubble runs into the torus, giving the inner bubble

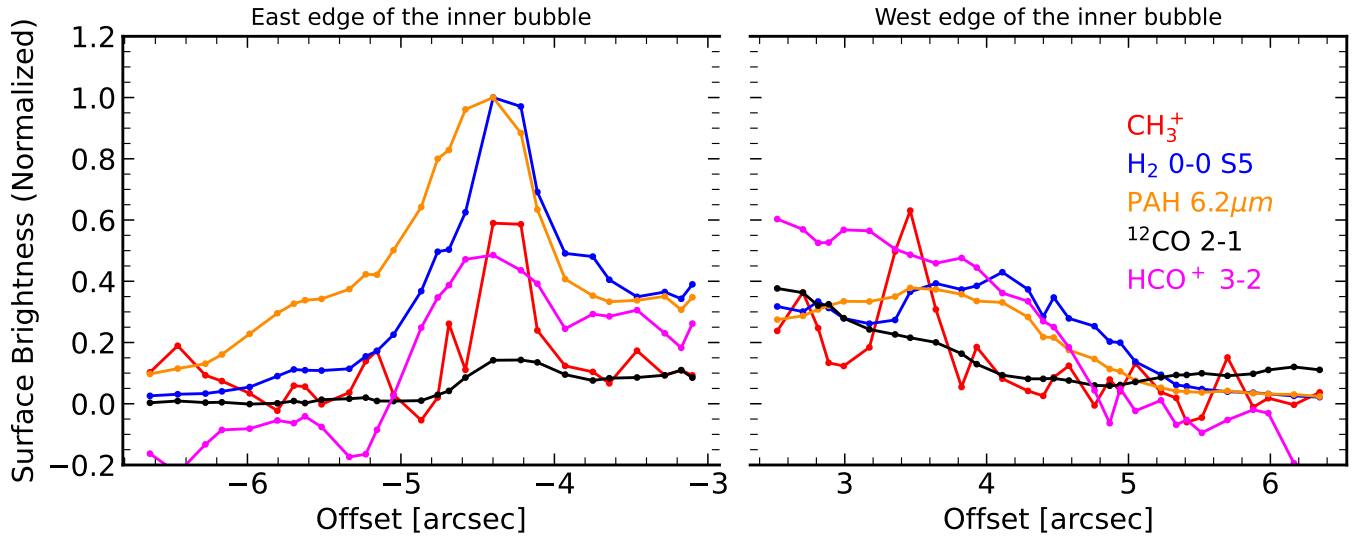


Figure 9. Normalized surface brightness profiles of CH_3^+ , H_2 , PAH $6.2\ \mu\text{m}$ (by Clark et al., in prep), CO and HCO^+ (by Moraga Baez et al., 2025, under review) along the cut. Offset is measured in arcsec from the position of the central star (R.A. = $17^{\text{h}}:13^{\text{m}}:44.488 \pm 0.004^{\text{s}}$, Dec. = $-37^{\circ}:06':11.76 \pm 0.03'$).

477 its characteristic peanut shape and creating regions of higher
 478 gas density. Point A (region around apertures 1,2, and 12),
 479 exhibiting the brightest CH_3^+ emission, is located at the inter-
 480 section of the inner bubble with the rear side of the torus.
 481 A corresponding bright feature is not observed where the inner
 482 bubble intersects the front side because of the extinction
 483 by the dust in the torus. However, enhanced emission is detected
 484 in both the east (aperture 7) and west (apertures 5 and
 485 6) of this intersection, potentially tracing redirected material
 486 emerging from the intersection. This spot on the west is design-
 487 ated point B. Apart from higher gas density, secondary
 488 factors may also contribute to enhanced formation rates. For
 489 example, at point A, the H I emission is several times brighter
 490 than the surrounding regions, suggesting higher UV flux, and
 491 point B coincides with a brighter H_2 emission that could
 492 boost CH_3^+ production.

493 In contrast, the outer bubble shows column densities an order
 494 of magnitude lower than typical values in the inner bubble
 495 and the torus and two orders of magnitude lower than point
 496 A. This is likely due to the lower column density of CO in the
 497 outer bubble. Interestingly, the CH_3^+ excitation temperature
 498 is significantly higher in the outer bubble (1000-2000K) than
 499 what is found in the inner bubble and torus (500-800K). The
 500 chemical pumping model by M. Zannese et al. (2025) shows
 501 that higher excitation temperature of CH^+ results from en-
 502 hanced H_2 level population densities, which occur when H_2
 503 is more efficiently FUV-pumped to higher vibrational states.
 504 Similarly, hotter CH_3^+ can form if the H_2 involved in hydro-
 505 gen abstraction reactions is vibrationally excited to higher
 506 levels. This indicates that the outer bubble is less shielded
 507 than the inner structures.

5.3. Chemistry initiated by CH_3^+

508 The main takeaway from the CH_3^+ detection in NGC 6302
 509 is recognizing that hydrocarbon radical chemistry, previously
 510 overlooked in oxygen-rich environments, should be incorpo-
 511 rated into planetary nebula chemical models. CH_3^+ drives
 512 gas-phase carbon chemistry through exothermic ion-neutral
 513 reactions, with models showing it can facilitate the forma-
 514 tion of numerous species, including CN, HCN, CH_2CO^+ ,
 515 CH_3OH , H_2CO , $\text{C}_2\text{H}_5\text{OH}$, CH_3OCH_3 , H_2CN^+ , etc. (see Fig.
 516 2 by D. Smith (1992) for the summary of the chemical net-
 517 work initiated by CH_3^+).

518 Spatial coincidences in NGC 6302 suggest potential con-
 519 nections between CH_3^+ and other observed species that war-
 520 rant consideration in chemical models. CH_3^+ is spatially
 521 coincident with HCO^+ along the inner and outer bubble
 522 edges (see Fig. 10), consistent with the exothermic reac-
 523 tion $\text{CH}_3^+ + \text{O} \rightarrow \text{HCO}^+ + \text{H}_2$ (G. B. I. Scott et al. 2000).
 524 The co-location of CH_3^+ with PAHs (see Fig. 11) raises the
 525 question whether CH^+ or CH_3^+ might initiate chemistry rel-
 526 evant to PAH formation. M. Agúndez et al. (2008) reported
 527 that strong FUV/X-ray radiation can efficiently drive carbon
 528 chemistry in dense O-rich gas where CH^+ and CH_3^+ can fur-
 529 ther react with e^- , C, and H_2 to form C_2H_2 , which can then
 530 initiate the chemistry leading to aromatic species like PAHs
 531 if activation energies are overcome. Since PAH emission
 532 is widespread in NGC 6302's central region—including the
 533 torus, inner and outer bubbles where CH_3^+ is detected—the
 534 role of CH_3^+ in the bottom-up PAH formation sequence
 535 should be investigated.

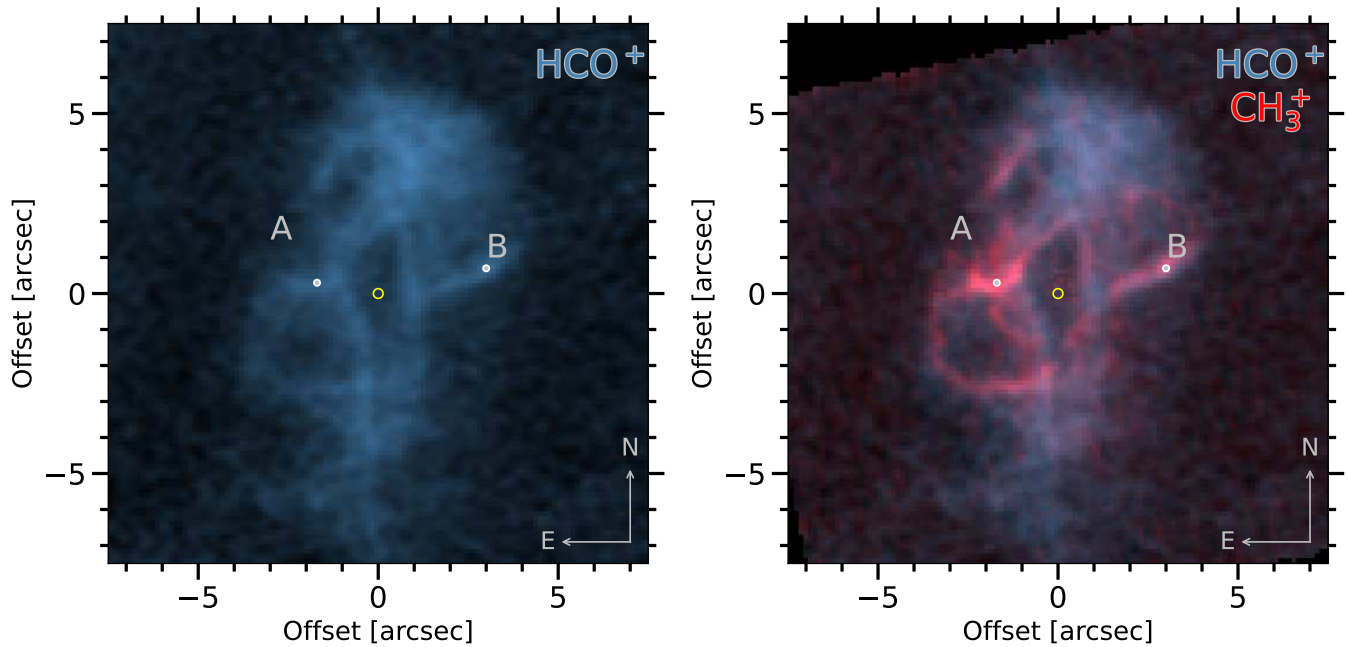


Figure 10. HCO^+ map (by Moraga Baez et al., 2025, under review) is shown in blue on the left and an overlay of CH_3^+ map is shown in red on the right. Locations marked by A and B represent the two bright spots on CH_3^+ map. The maps are centred at the central star (RA=17:13:44.488±0.004, dec=-37:06:11.76±0.03) whose position is indicated by the white circle at the center.

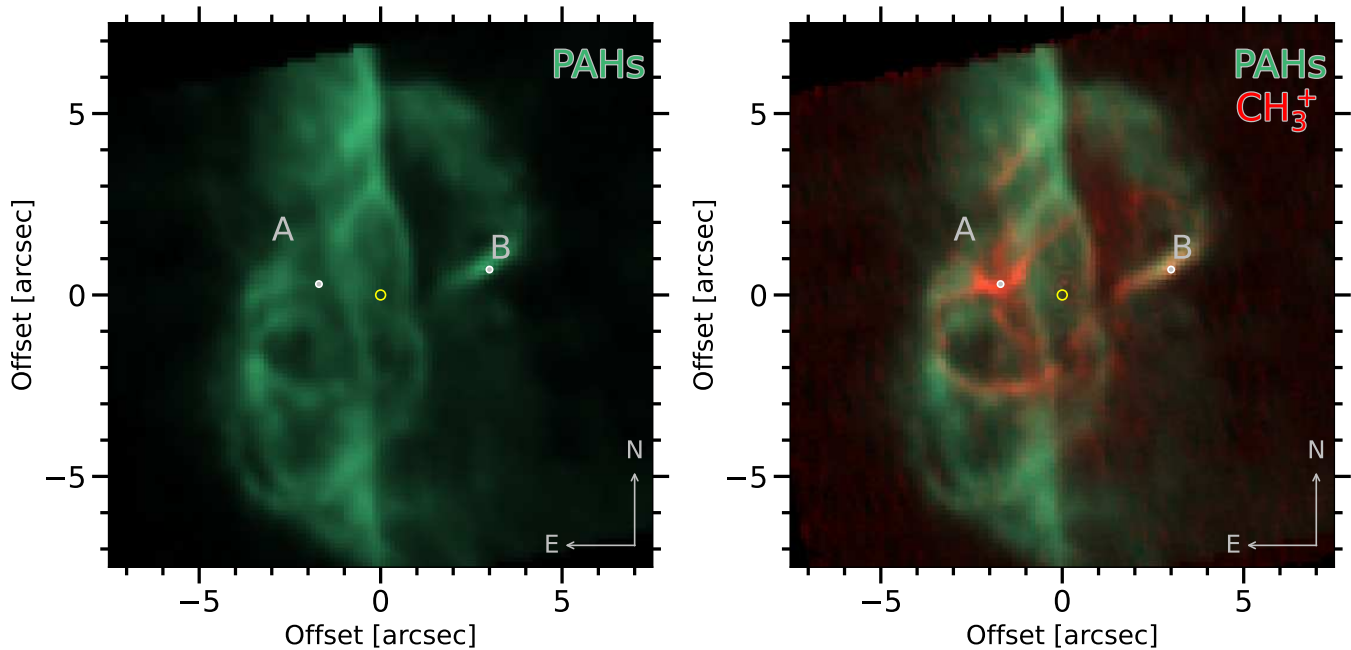


Figure 11. The PAH map (by Clark et al., in prep) here on the left shows the integrated intensity of the $6.2\ \mu\text{m}$ feature (integrated over the $6.12\text{--}6.5\ \mu\text{m}$ range after continuum subtraction). A comparison with CH_3^+ map is shown on the right. Locations marked by A and B represent the two bright spots on CH_3^+ map. The maps are centred at the central star (R.A.= $17^{\text{h}}:13^{\text{m}}:44.488 \pm 0.004^{\text{s}}$, Dec. = $-37^{\circ}:06':11.76 \pm 0.03''$) whose position is indicated by the white circle at the center.

6. SUMMARY & CONCLUSIONS

537

538 We report the detection of methyl cation (CH_3^+) in JWST-
539 MIRI observations of the O-rich planetary nebula NGC 6302,

540 marking the first identification of this key organic precursor

541 in such an environment. We investigated the nature of the

542 CH_3^+ emission and its relation to other species such as ^{12}CO ,

543 H₂, PAHs and HCO⁺. We fit the observed CH₃⁺ emission
 544 with LTE models to derive excitation temperature and col-
 545 umn density. Model fits reproduce the CH₃⁺ emission very
 546 well, yielding excitation temperatures of 500-800K in the in-
 547 ner bubble and the torus, significantly higher excitation tem-
 548 perature of 1000-2000K in the outer bubble. Column den-
 549 sities of CH₃⁺ in the excited state are typically ~10¹² cm⁻²
 550 ranging from ~10¹¹ cm⁻² in the outer bubble to ~10¹³ cm⁻²
 551 where the inner bubble runs into the torus. These measure-
 552 ments represent only a fraction of the total population due
 553 to non-LTE chemical pumping. The spatial coincidence of
 554 CH₃⁺ with ¹²CO and H₂ supports its formation via chemical
 555 pumping in the UV-irradiated O-rich gas.

556 The presence of CH₃⁺ in this O-rich PN highlights the car-
 557 bon chemistry at play in O-rich environments under strong
 558 UV irradiation. These results indicate that hydrocarbon rad-
 559 ical chemistry must be incorporated into chemical models
 560 of PNe. Further observations at comparable spatial resolu-
 561 tion, particularly in the near-IR (which is rich in molecular
 562 features), are essential to unravel the different chemical net-
 563 works involved in this chemistry.

564 ACKNOWLEDGMENTS

565 This work is based on observations made with the
 566 NASA/ESA/CSA James Webb Space Telescope. All of the
 567 data presented in this article were obtained from the Mikul-
 568 ski Archive for Space Telescopes (MAST) at the Space Tele-
 569 scope Science Institute. The data of this specific observing
 570 program can be accessed via [doi:10.17909/s1rn-1t84](https://doi.org/10.17909/s1rn-1t84). This
 571 study is based on the international consortium of ESSENcE
 572 (Evolved Stars and their Nebulae in the JWST era). This

573 article/publication is based upon work from COST Action
 574 NanoSpace, CA21126, supported by COST (European Co-
 575 operation in Science and Technology).

576 C.B, J.C., E.P. and N.C. acknowledge support from the
 577 University of Western Ontario, the Canadian Space Agency
 578 (CSA)[22JWGO1-22], and the Natural Sciences and En-
 579 gineering Research Council of Canada. M.M. and R.W.
 580 acknowledge support from the STFC Consolidated grant
 581 (ST/W000830/1). M.J.B. and R.W. acknowledge support
 582 from the European Research Council (ERC) Advanced Grant
 583 SNDUST 694520. A.A.Z. acknowledges funding through
 584 UKRI/STFC through grant ST/T000414/1. H.L.D. acknowl-
 585 edges support from grant JWST-GO-01742.004 and NSF
 586 grants 1715332 and 2307117. N.C.S. acknowledges support
 587 from NSF award AST-2307116. G. G.-S. thanks Michael
 588 L. Norman and the Laboratory for Computational Astro-
 589 physics for the use of ZEUS-3D. The computations were
 590 performed at the Instituto de Astronomía-UNAM at En-
 591 senada. P.J.K. acknowledges support from the Science
 592 Foundation Ireland/Irish Research Council Pathway pro-
 593 gramme under Grant Number 21/PATH-S/9360. R.S.'s con-
 594 tribution to the research described here was carried out at
 595 the Jet Propulsion Laboratory, California Institute of Tech-
 596 nology, under a contract with NASA. K.E.K. acknowl-
 597 edges support from grant JWST-GO-01742.010-A. F.K. and
 598 M.T. acknowledge support from the Spanish Ministry of
 599 Science, Innovation and Universities, under grant number
 600 PID2023-149918NB-I00. This research was also partly
 601 supported by the Spanish program Unidad de Excelen-
 602 cia María de Maeztu CEX2020-001058-M, financed by
 603 MCIN/AEI/10.13039/501100011033. JML was supported
 604 by basic research funds of the Office of Naval Research.

605 APPENDIX

606 A. CONTINUUM

607 An example of the continuum adopted for fitting the CH₃⁺
 608 spectral features is shown in Fig. 12.

610 B. H₂ MAP WITH APERTURES

611 The 25 apertures used to sample the CH₃⁺ emission across
 612 distinct regions are plotted on the H₂ map in Fig. 13.

614 C. BAND RATIO METHOD

615 The best-fit Gaussians to the 7.15 μm and 7.2 μm bands
 616 for all 25 apertures are shown in Figs. 14 and 15, respec-
 617 tively. These are used to determine the excitation temperature
 618 of CH₃⁺ using the band ratio method as described in Sec. 4.

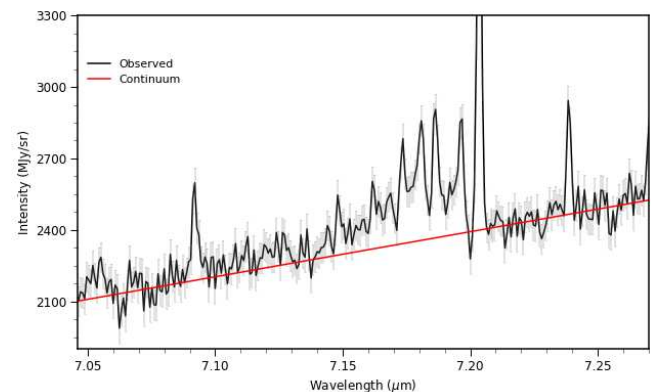


Figure 12. JWST MIRI spectrum at aperture 1 (in black). The red line provides an example of the continuum adopted to fit the models to the observations.

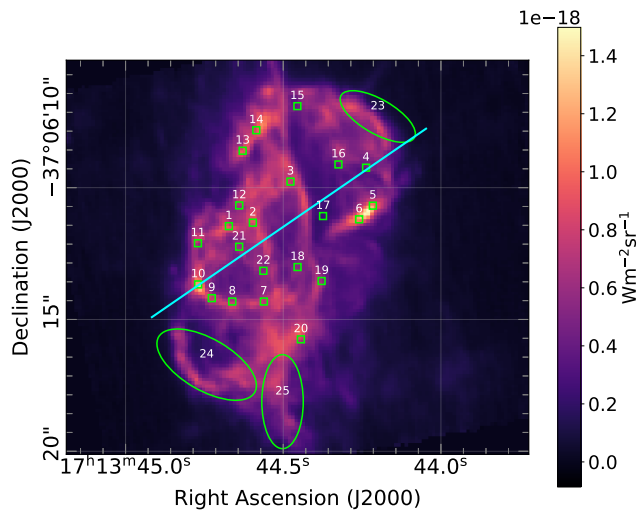


Figure 13. Integrated surface brightness map of H_2 0-0 S(5) line at $6.908 \mu\text{m}$. The green boxes and ellipses represent the 25 apertures used to study CH_3^+ emission in detail.

619

D. FIT RESULTS

620 The best-fit models for determining CH_3^+ temperature and
 621 column density in all 25 apertures are shown in Fig. 16. See
 622 Sec. 4 for details on the fitting procedure.

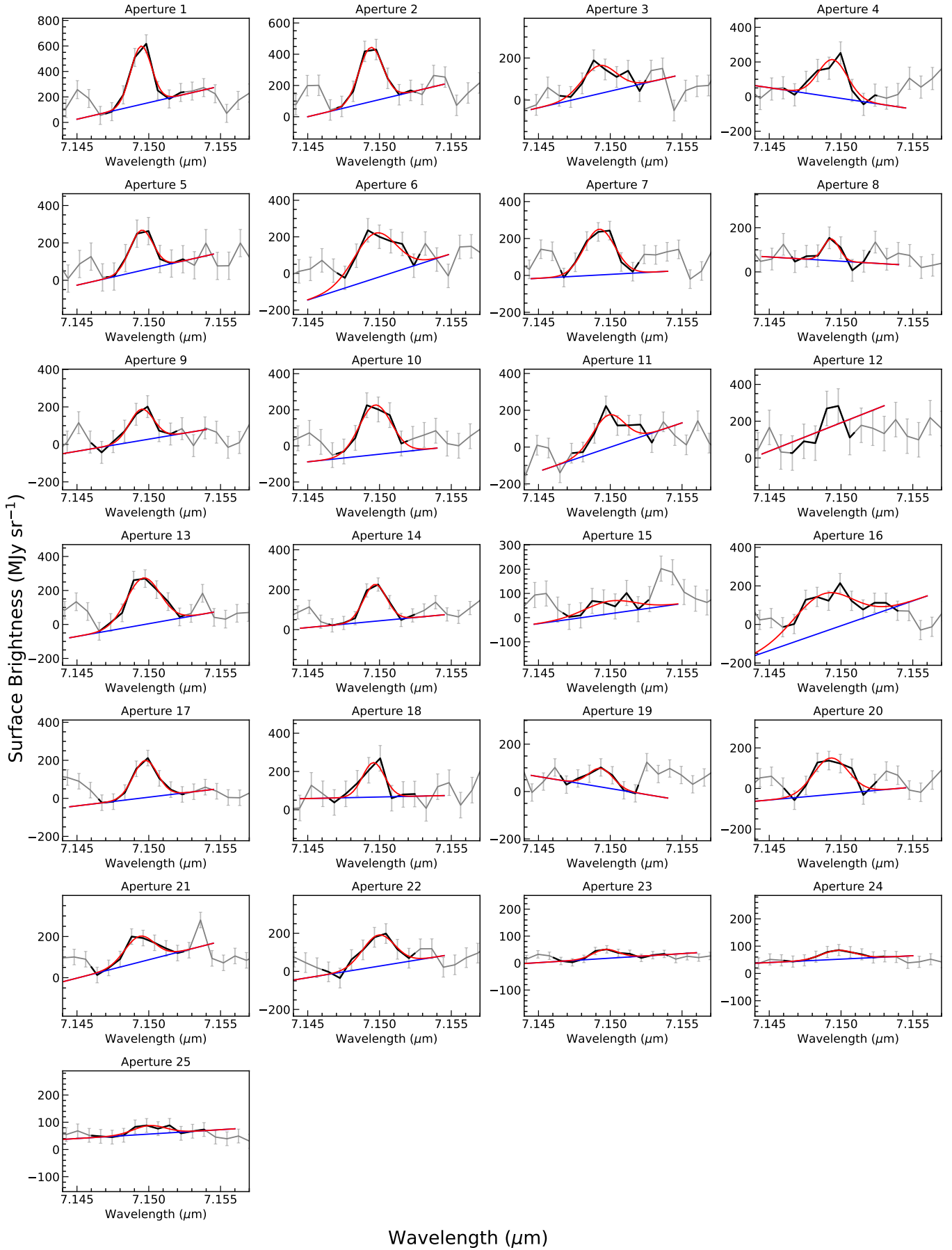


Figure 14. Gaussian fits to the 7.15 band used for the band ratio method to determine the temperature. The **integrated surface brightness** value at each aperture is listed in Table 1.

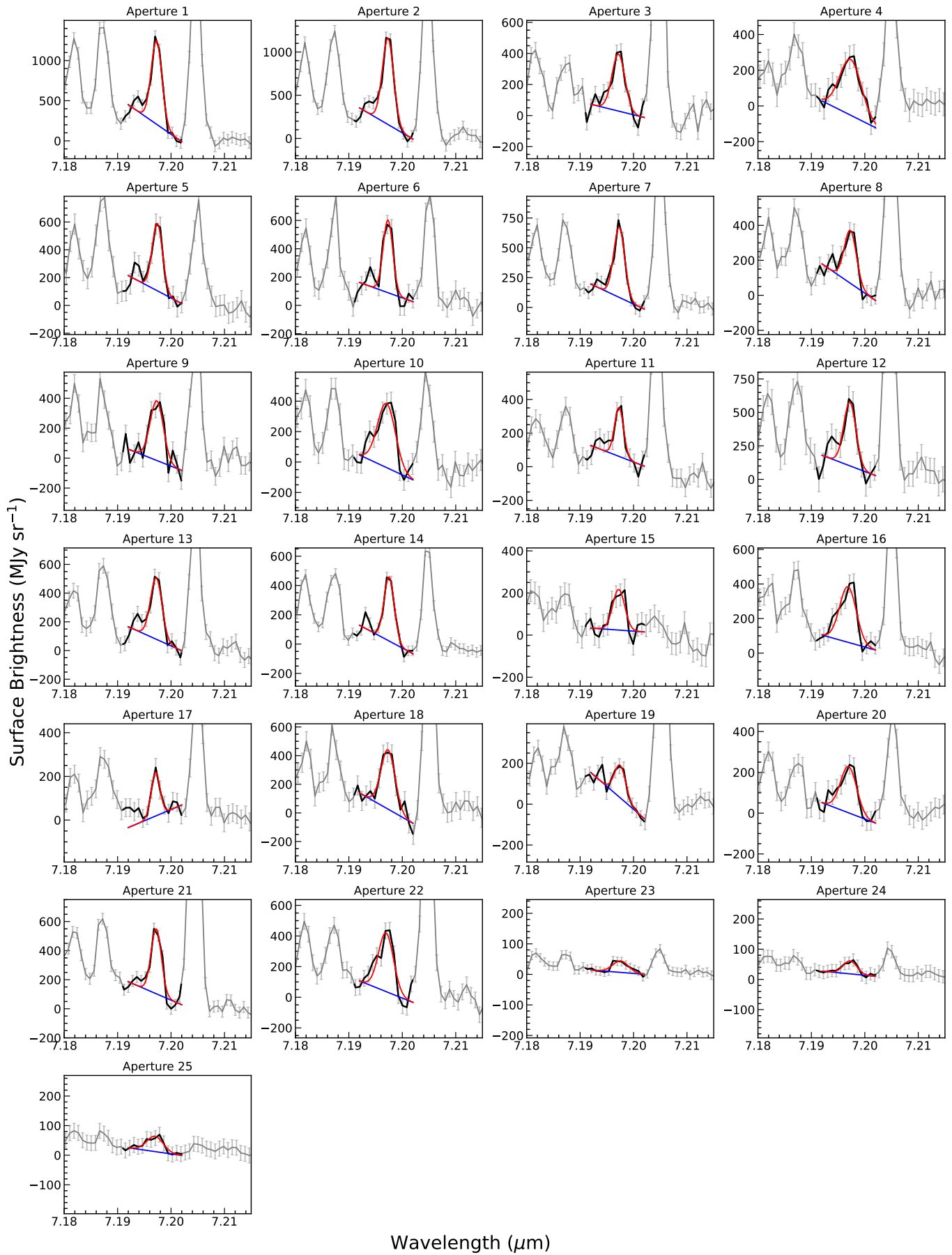
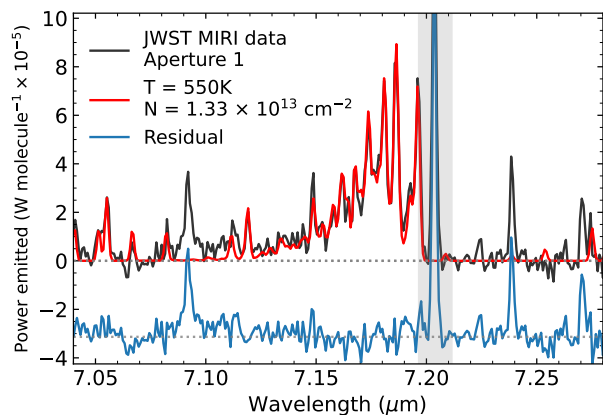
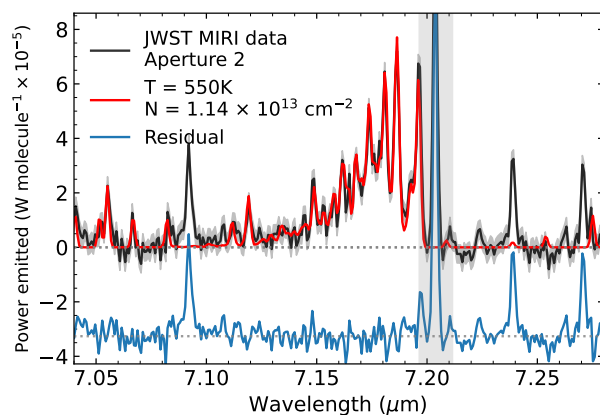


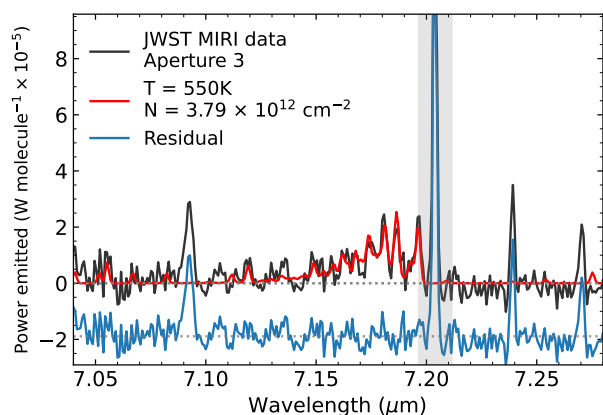
Figure 15. Gaussian fits to the 7.2 band used for the band ratio method to determine the temperature. The **integrated surface brightness** value at each aperture is listed in Table 1.



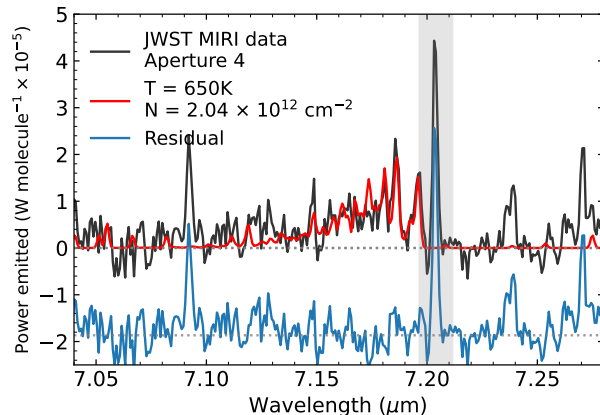
(a) Aperture 1.



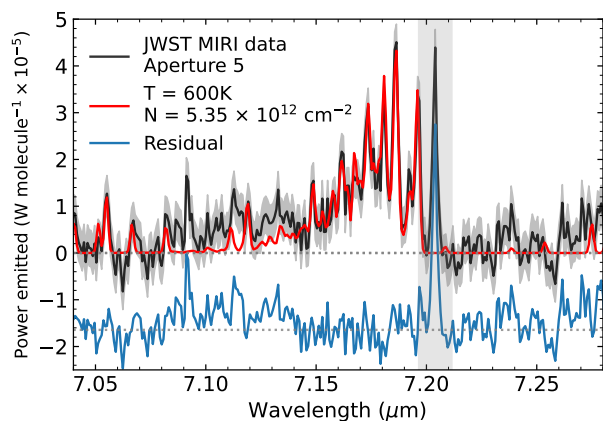
(b) Aperture 2.



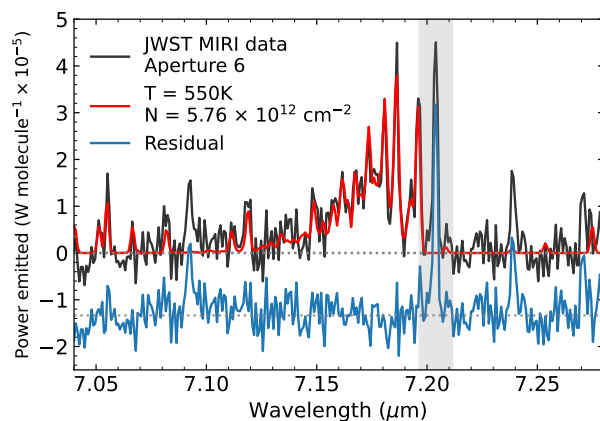
(c) Aperture 3.



(d) Aperture 4.

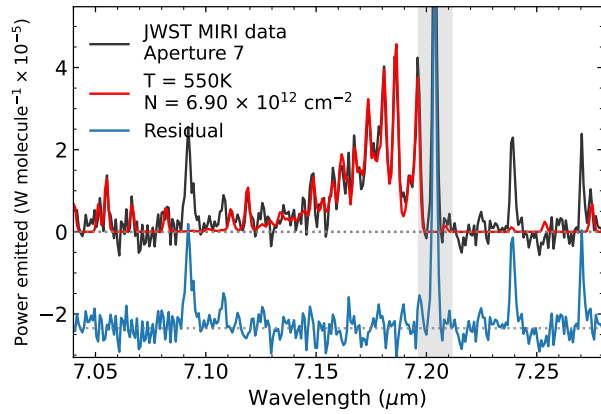


(e) Aperture 5.

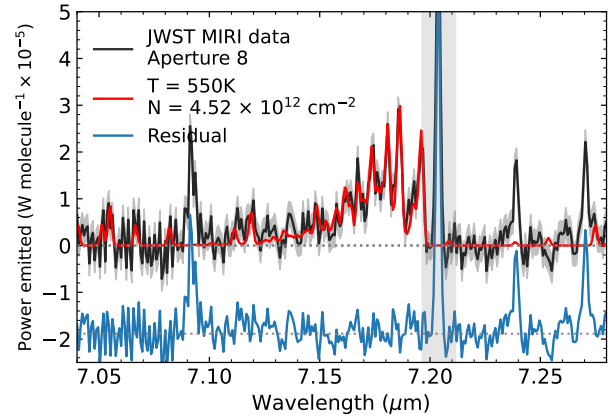


(f) Aperture 6.

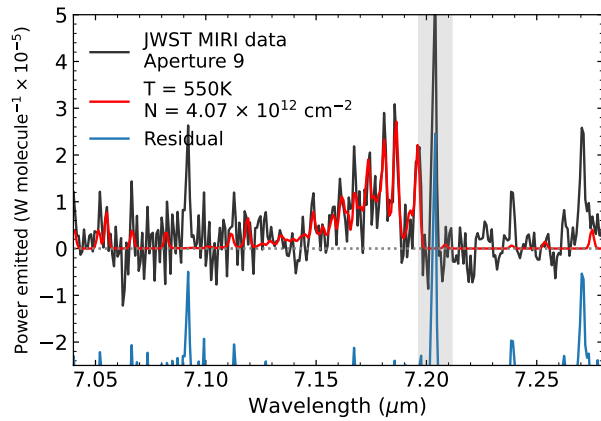
Figure 16. Observations (black), best-fit model (red), and residuals (blue) for each aperture.



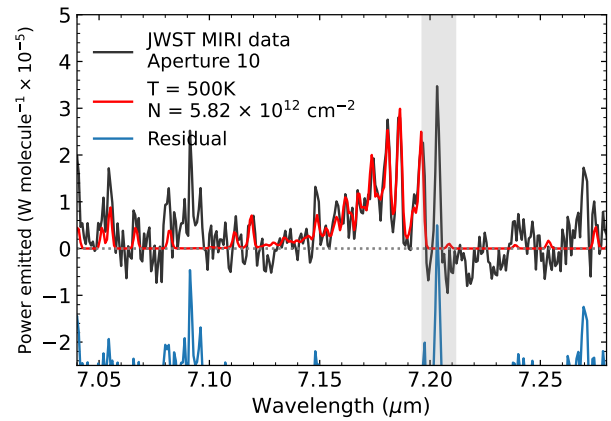
(g) Aperture 7.



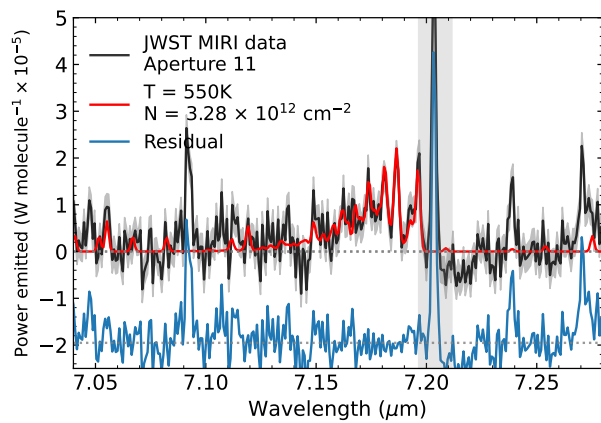
(h) Aperture 8.



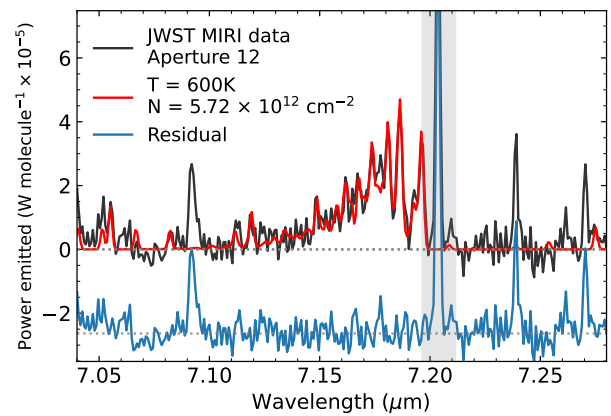
(i) Aperture 9.



(j) Aperture 10.

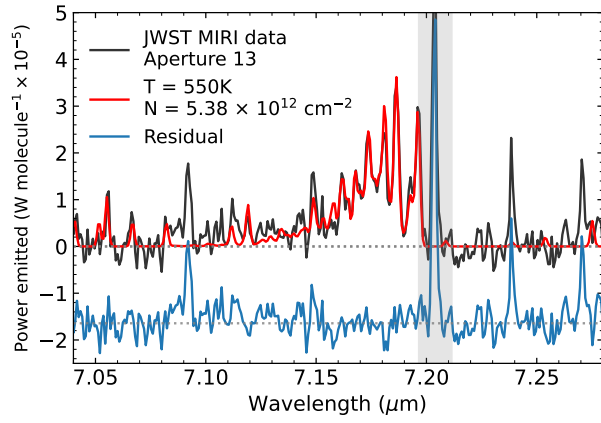


(k) Aperture 11.

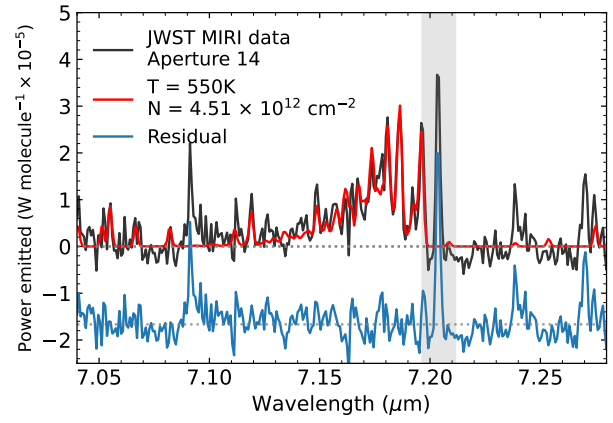


(l) Aperture 12.

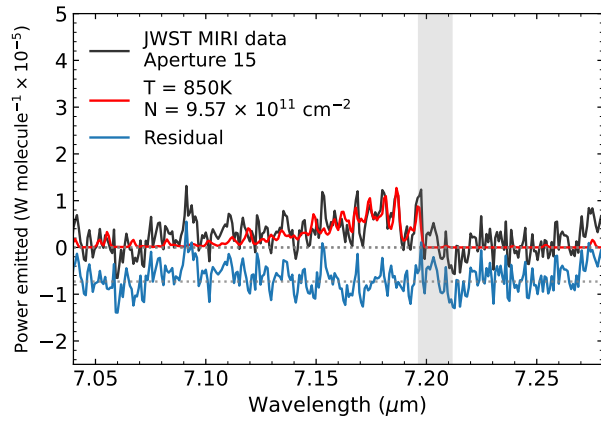
Figure 16. Figure 16 (continued).



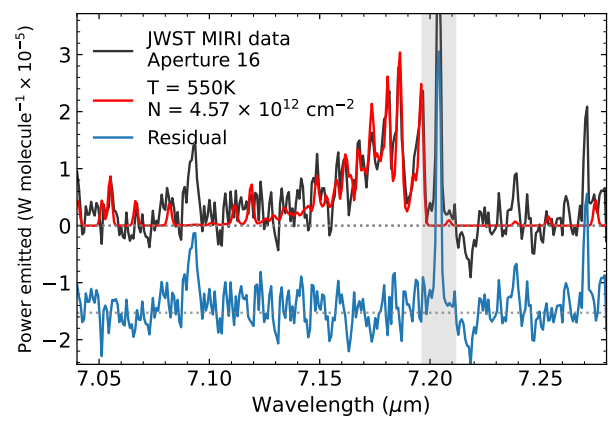
(m) Aperture 13.



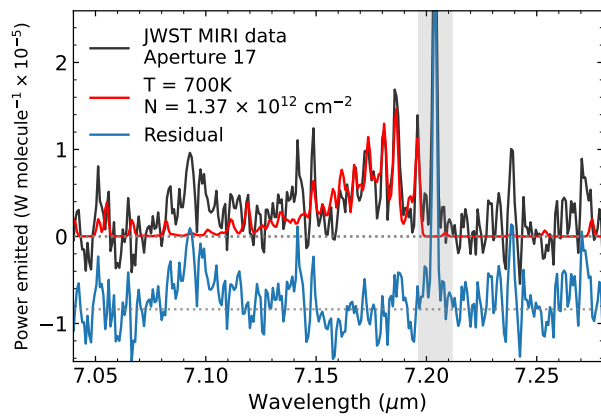
(n) Aperture 14.



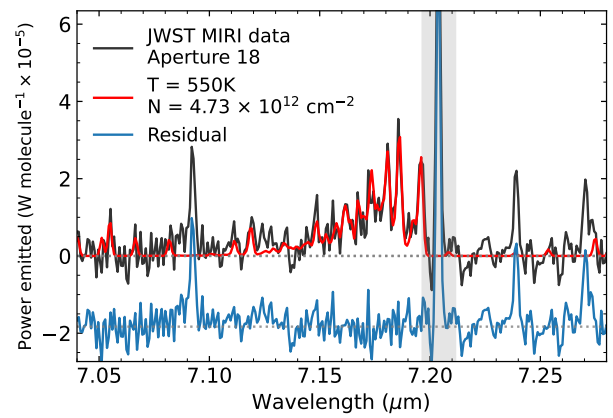
(o) Aperture 15.



(p) Aperture 16.

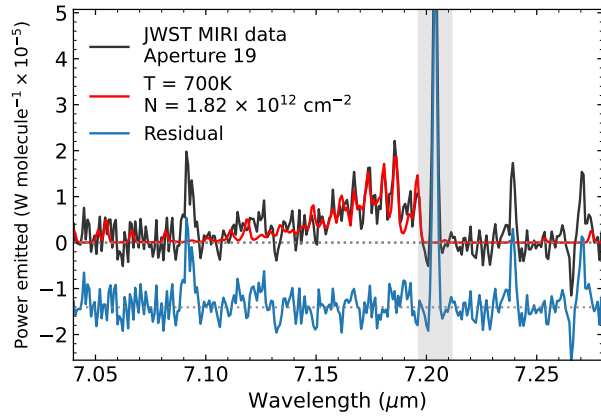


(q) Aperture 17.

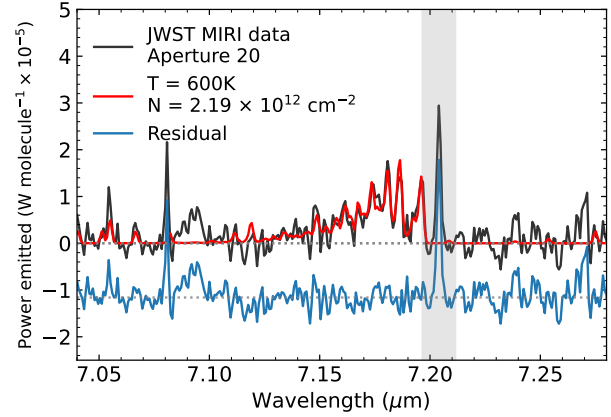


(r) Aperture 18.

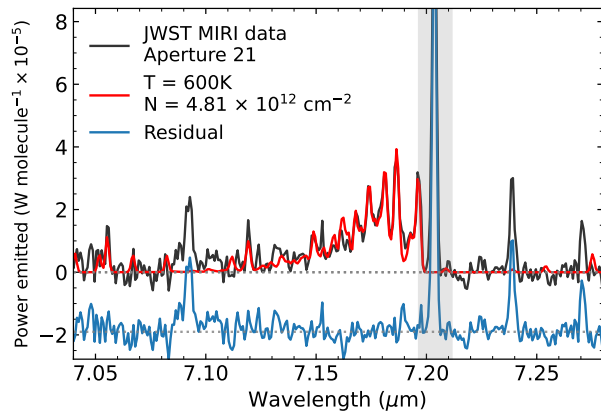
Figure 16. Figure 16 (continued).



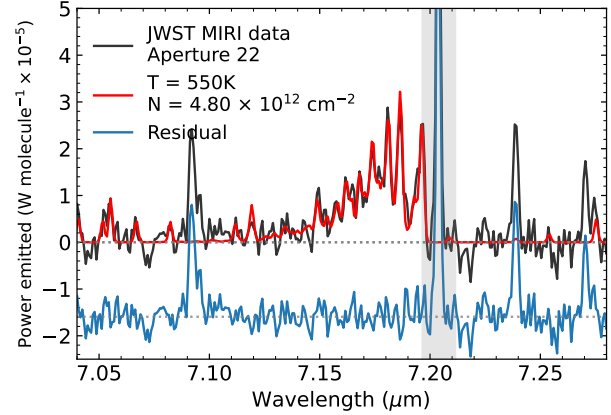
(s) Aperture 19.



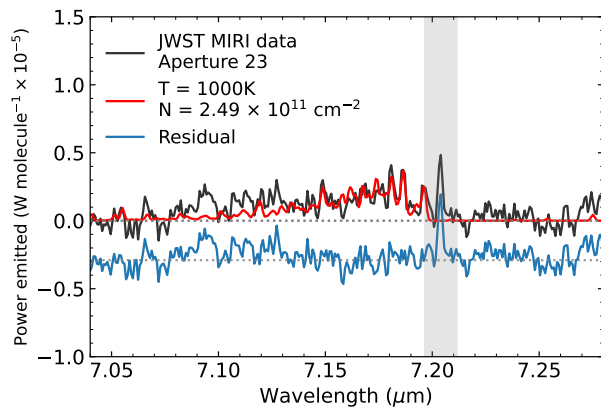
(t) Aperture 20.



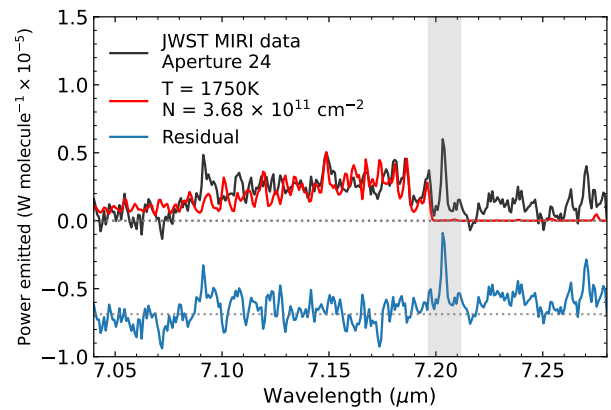
(u) Aperture 21.



(v) Aperture 22.

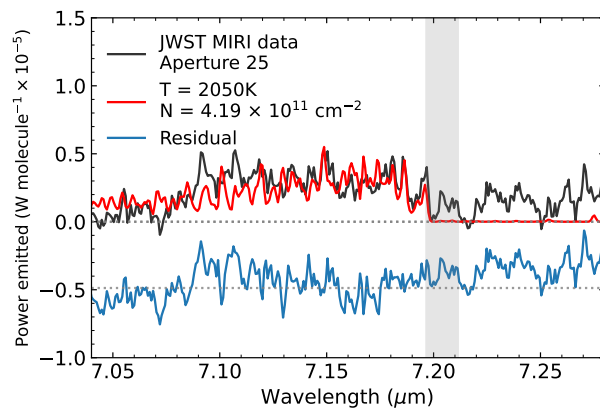


(u) Aperture 23.



(v) Aperture 24.

Figure 16. Figure 16 (continued).



(s) Aperture 25.

Figure 16. Figure 16 (continued).

REFERENCES

- 623 Agúndez, M. 2022, in European Physical Journal Web of
624 Conferences, Vol. 265, European Physical Journal Web of
625 Conferences, 00029, doi: [10.1051/epjconf/202226500029](https://doi.org/10.1051/epjconf/202226500029)
- 626 Agúndez, M., Cernicharo, J., & Goicoechea, J. R. 2008, A&A,
627 483, 831, doi: [10.1051/0004-6361:20077927](https://doi.org/10.1051/0004-6361:20077927)
- 628 Agúndez, M., Cernicharo, J., & Guélin, M. 2014, A&A, 570, A45,
629 doi: [10.1051/0004-6361/201424542](https://doi.org/10.1051/0004-6361/201424542)
- 630 Agúndez, M., Goicoechea, J. R., Cernicharo, J., Faure, A., &
631 Roueff, E. 2010, ApJ, 713, 662,
632 doi: [10.1088/0004-637X/713/1/662](https://doi.org/10.1088/0004-637X/713/1/662)
- 633 Araki, M. 2025, Molecules in Space – List of Observed Interstellar
634 Molecules,, <http://molecules-in.space/>
- 635 Argyriou, I., Glasse, A., Law, D. R., et al. 2023, A&A, 675, A111,
636 doi: [10.1051/0004-6361/202346489](https://doi.org/10.1051/0004-6361/202346489)
- 637 Balick, B., Borchert, L., Kastner, J. H., et al. 2023, ApJ, 957, 54,
638 doi: [10.3847/1538-4357/acf5ea](https://doi.org/10.3847/1538-4357/acf5ea)
- 639 Berné, O., Martin-Drumel, M.-A., Schroetter, I., et al. 2023,
640 Nature, 621, 56, doi: [10.1038/s41586-023-06307-x](https://doi.org/10.1038/s41586-023-06307-x)
- 641 Black, J. H., & Dalgarno, A. 1977, ApJS, 34, 405,
642 doi: [10.1086/190455](https://doi.org/10.1086/190455)
- 643 Cami, J. 2002, PhD thesis, University of Amsterdam
- 644 Cami, J., Bernard-Salas, J., Peeters, E., & Malek, S. E. 2010,
645 Science, 329, 1180, doi: [10.1126/science.1192035](https://doi.org/10.1126/science.1192035)
- 646 Casassus, S., Roche, P. F., & Barlow, M. J. 2000, MNRAS, 314,
647 657, doi: [10.1046/j.1365-8711.2000.03208.x](https://doi.org/10.1046/j.1365-8711.2000.03208.x)
- 648 Changala, P. B., Chen, N. L., Le, H. L., et al. 2023, A&A, 680,
649 A19, doi: [10.1051/0004-6361/202347765](https://doi.org/10.1051/0004-6361/202347765)
- 650 Cohen, M., Barlow, M. J., Liu, X. W., & Jones, A. F. 2002,
651 MNRAS, 332, 879, doi: [10.1046/j.1365-8711.2002.05350.x](https://doi.org/10.1046/j.1365-8711.2002.05350.x)
- 652 Cox, N. L. J., Pilleri, P., Berné, O., Cernicharo, J., & Joblin, C.
653 2016, in Journal of Physics Conference Series, Vol. 728, Journal
654 of Physics Conference Series (IOP), 032011,
655 doi: [10.1088/1742-6596/728/3/032011](https://doi.org/10.1088/1742-6596/728/3/032011)
- 656 De Beck, E., Kamiński, T., Patel, N. A., et al. 2013, A&A, 558,
657 A132, doi: [10.1051/0004-6361/201321349](https://doi.org/10.1051/0004-6361/201321349)
- 658 Decin, L., Richards, A. M. S., Danilovich, T., Homan, W., & Nuth,
659 J. A. 2018, A&A, 615, A28, doi: [10.1051/0004-6361/201732216](https://doi.org/10.1051/0004-6361/201732216)
- 660 Decin, L., De Beck, E., Brünken, S., et al. 2010, A&A, 516, A69,
661 doi: [10.1051/0004-6361/201014136](https://doi.org/10.1051/0004-6361/201014136)
- 662 Feibelman, W. A. 2001, ApJ, 550, 785, doi: [10.1086/319798](https://doi.org/10.1086/319798)
- 663 García-Hernández, D. A., Zamora, O., Yagüe, A., et al. 2013,
664 A&A, 555, L3, doi: [10.1051/0004-6361/201321818](https://doi.org/10.1051/0004-6361/201321818)
- 665 Godard, B., & Cernicharo, J. 2013, A&A, 550, A8,
666 doi: [10.1051/0004-6361/201220151](https://doi.org/10.1051/0004-6361/201220151)
- 667 Gómez-Gordillo, S., Akras, S., Gonçalves, D. R., & Steffen, W.
668 2020, MNRAS, 492, 4097, doi: [10.1093/mnras/staa060](https://doi.org/10.1093/mnras/staa060)
- 669 Hasegawa, T. I., & Kwok, S. 2001, ApJ, 562, 824,
670 doi: [10.1086/323856](https://doi.org/10.1086/323856)
- 671 Henning, T., Kamp, I., Samland, M., et al. 2024, PASP, 136,
672 054302, doi: [10.1088/1538-3873/ad3455](https://doi.org/10.1088/1538-3873/ad3455)
- 673 Herbst, E. 2021, Frontiers in Astronomy and Space Sciences, 8,
674 207, doi: [10.3389/fspas.2021.776942](https://doi.org/10.3389/fspas.2021.776942)
- 675 Höfner, S., & Olofsson, H. 2018, A&A Rev., 26, 1,
676 doi: [10.1007/s00159-017-0106-5](https://doi.org/10.1007/s00159-017-0106-5)
- 677 Kastner, J. H., Moraga Baez, P., Balick, B., et al. 2022, ApJ, 927,
678 100, doi: [10.3847/1538-4357/ac51cd](https://doi.org/10.3847/1538-4357/ac51cd)
- 679 Kim, H., Wyrowski, F., Menten, K. M., & Decin, L. 2010, A&A,
680 516, A68, doi: [10.1051/0004-6361/201014094](https://doi.org/10.1051/0004-6361/201014094)
- 681 Kwitter, K. B., & Henry, R. B. C. 2022, PASP, 134, 022001,
682 doi: [10.1088/1538-3873/ac32b1](https://doi.org/10.1088/1538-3873/ac32b1)
- 683 Matsuura, M., Zijlstra, A. A., Molster, F. J., et al. 2005, MNRAS,
684 359, 383, doi: [10.1111/j.1365-2966.2005.08903.x](https://doi.org/10.1111/j.1365-2966.2005.08903.x)
- 685 Matsuura, M., Bernard-Salas, J., Lloyd Evans, T., et al. 2014,
686 MNRAS, 439, 1472, doi: [10.1093/mnras/stt2495](https://doi.org/10.1093/mnras/stt2495)
- 687 McGuire, B. A. 2022, ApJS, 259, 30,
688 doi: [10.3847/1538-4365/ac2a48](https://doi.org/10.3847/1538-4365/ac2a48)
- 689 Meisner, J., Hallmen, P. P., Kästner, J., & Rauhut, G. 2019,
690 J. Chem. Phys., 150, 084306, doi: [10.1063/1.5084100](https://doi.org/10.1063/1.5084100)
- 691 Nagy, Z., Van der Tak, F. F. S., Ossenkopf, V., et al. 2013, A&A,
692 550, A96, doi: [10.1051/0004-6361/201220519](https://doi.org/10.1051/0004-6361/201220519)
- 693 Newville, M., Stensitzki, T., Allen, D. B., & Ingargiola, A. 2014,
694 LMFIT: Non-Linear Least-Square Minimization and
695 Curve-Fitting for Python, 0.8.0 Zenodo,
696 doi: [10.5281/zenodo.11813](https://doi.org/10.5281/zenodo.11813)
- 697 Perea-Calderón, J. V., García-Hernández, D. A., García-Lario, P.,
698 Szczerba, R., & Bobrowsky, M. 2009, A&A, 495, L5,
699 doi: [10.1051/0004-6361/200811457](https://doi.org/10.1051/0004-6361/200811457)
- 700 Peretto, N., Fuller, G., Zijlstra, A., & Patel, N. 2007, A&A, 473,
701 207, doi: [10.1051/0004-6361:20066973](https://doi.org/10.1051/0004-6361:20066973)
- 702 Posch, T., Kerschbaum, F., Mutschke, H., Dorschner, J., & Jäger,
703 C. 2002, A&A, 393, L7, doi: [10.1051/0004-6361:20021127](https://doi.org/10.1051/0004-6361:20021127)
- 704 Santander-García, M., Bujarrabal, V., Alcolea, J., et al. 2017,
705 A&A, 597, A27, doi: [10.1051/0004-6361/201629288](https://doi.org/10.1051/0004-6361/201629288)
- 706 Scott, G. B. I., Milligan, D. B., Fairley, D. A., Freeman, C. G., &
707 McEwan, M. J. 2000, J. Chem. Phys., 112, 4959,
708 doi: [10.1063/1.481050](https://doi.org/10.1063/1.481050)
- 709 Smith, D. 1992, Chemical Reviews, 92, 1473,
710 doi: [10.1021/cr00015a001](https://doi.org/10.1021/cr00015a001)
- 711 Stanghellini, L., García-Hernández, D. A., García-Lario, P., et al.
712 2012, ApJ, 753, 172, doi: [10.1088/0004-637X/753/2/172](https://doi.org/10.1088/0004-637X/753/2/172)
- 713 Sternberg, A., & Dalgarno, A. 1995, ApJS, 99, 565,
714 doi: [10.1086/192198](https://doi.org/10.1086/192198)
- 715 Sylvester, R. J., Kemper, F., Barlow, M. J., et al. 1999, A&A, 352,
716 587, doi: [10.48550/arXiv.astro-ph/9910368](https://doi.org/10.48550/arXiv.astro-ph/9910368)
- 717 Tielens, A. G. G. M. 2013, Reviews of Modern Physics, 85, 1021,
718 doi: [10.1103/RevModPhys.85.1021](https://doi.org/10.1103/RevModPhys.85.1021)

- 719 Waters, L. B. F. M., Beintema, D. A., Zijlstra, A. A., et al. 1998a,
720 A&A, 331, L61, doi: [10.48550/arXiv.astro-ph/9802289](https://doi.org/10.48550/arXiv.astro-ph/9802289)
- 721 Waters, L. B. F. M., Cami, J., de Jong, T., et al. 1998b, Nature, 391,
722 868, doi: [10.1038/36052](https://doi.org/10.1038/36052)
- 723 Wells, M., Pel, J. W., Glasse, A., et al. 2015, PASP, 127, 646,
724 doi: [10.1086/682281](https://doi.org/10.1086/682281)
- 725 Western, C. M. 2017, J. Quant. Spec. Radiat. Transf., 186, 221,
726 doi: [10.1016/j.jqsrt.2016.04.010](https://doi.org/10.1016/j.jqsrt.2016.04.010)
- 727 Wright, N. J., Barlow, M. J., Ercolano, B., & Rauch, T. 2011,
728 MNRAS, 418, 370, doi: [10.1111/j.1365-2966.2011.19490.x](https://doi.org/10.1111/j.1365-2966.2011.19490.x)
- 729 Zannese, M., Tabone, B., Habart, E., et al. 2025, A&A, 696, A99,
730 doi: [10.1051/0004-6361/202453441](https://doi.org/10.1051/0004-6361/202453441)
- 731 Zhang, Y., & Kwok, S. 2011, ApJ, 730, 126,
732 doi: [10.1088/0004-637X/730/2/126](https://doi.org/10.1088/0004-637X/730/2/126)
- 733 Zijlstra, A. A., Gaylard, M. J., te Lintel Hekkert, P., et al. 1991,
734 A&A, 243, L9